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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking The Russian Federation State Research Center - All Russian Electrotechnical Institute as follows: A non-relativistic beam-plasma microwave amplifier (Plasma-Filled TWT) based on a hybrid coupled-cavity slow-wave structure (CCSWS) with a plasma-filled transit channel has been developed in VEI. Needed improvements of these microwave tubes for their commercial and industrial applications in communication systems and microwave technology require special investigations of the main features of these tubes including noise and spectral purity parameters, and hybrid slow-wave structure electrodynamics. This is the goal of the present work.□□To elaborate, a plasma-filled coupled cavity traveling-wave tube (CCTWT) amplifier, designed as a sealed tube, is characterized by a combination of high efficiency (30%), and high output microwave power (up to 20 kW). It is not available in the comparable vacuum TWT. At the same time, commercial applications of plasma-filled TWTs, as a new type of microwave tube, demands theoretical and experimental investigations of a number of specific parameters such as low-level of its own self-generated noise, spectral purity characteistics, minimal phase instability, and high quality of amplitude-dynamic and amplitue-frequency diagrams. The work proposes to investigate a number of issues for improvement of the plasma TWT's operating parameters and determination of the possibliity of the plasma microwave tube's application in communications systems and microwave technology. Much of this work will be done in conjunction with the Institute for Plasma Research at the University of Maryland in the USA.

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# "Investigation of Characteristics of High-Power Wide-Band Plasma-Filled Traveling Wave Tubes (TWT)"

**Final Report on ISTC Project 2347p ( 007037 )**

**(August 1, 2002 – January 31, 2004 )**

**General Director GUP VEI** **Victor Kovalev**

May 24, 2004

**Project Manager** **V. Perevodchikov**

May 24, 2004



Moscow, May 2004

# FINAL REPORT

## "Investigation of Characteristics of High-Power Wide-Band Plasma-Filled Traveling Wave Tubes (TWT)"

**Project # 2347p**

**(August 1, 2002 – January 31, 2004 )**

The Leading Institution -

**The State Unitary Enterprise**

**"All-Russian Electrotechnical Institute named after V.I. Lenin"**

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The results of theoretical and experimental researches of physical processes in the plasma-beam hybrid electro dynamic structures, of basic characteristics of beam-plasma microwave tubes (plasma TWT) are submitted, estimation of an opportunity of their application in communication systems and also in the microwave technologies is given.

**Key words**: plasma microwave electronics, traveling wave tube (TWT), electronic optics, electron beam, beam-plasma interaction, chain of coupled-cavity resonators (CCC), hybrid slow wave structure (SWS), microwave energy input and output systems, "warm" tests of SWS, mathematic simulation, dispersion characteristics, amplitude-frequency and dynamic characteristics, self-noise and out-of-band oscillations.

# Contents

# I. Introduction

Scientific and engineering works on given Project are connected with researches of physics and technical problems and technologies in a new field of power microwave electronics – plasma microwave electronics.

I t is well known that the birth of plasma microwave electronics dates back to 1949 when the scientists in the USSR (A.I.Akhiezer and Ja.B. Fainberg) and in the USA (D.Bohm and E.Gross) for the first time investigated the excitation of electromagnetic waves in a plasma through a beam-plasma instability. During the past years there have been substantial advances in non-relativistic plasma microwave electronics. At VEI a non-relativistic beam-plasma amplifier of Cherenkov's type (plasma filled TWT) is being developed. The hybrid slow wave structure of such amplifier consists of chain of coupled-cavity resonators (CCC) with plasma filling of transit channel.

A cylindrical beam-plasma column (plasma density up to $5x10^{11}$ $cm^{-3}$ - $1x10^{12}$ , electron temperature ≈ 20 eV) is created by the electron beam ( 3 A, 20 keV) as a result of beam ionization of working gas ($7 \times 10^{-4} - 1 \times 10^{-3}$ Torr). Plasma CC TWT in centimeters wave-length, designed as a sealed tube, are characterized by a combination of high efficiency (30%), wide band-width, high output power (up to 20 kW) having no analogous devices in traditional vacuum microwave electronics.

**The purpose of the project:** theoretical and experimental researches of physical processes in beam-plasma hybrid electrodynamic systems, the basic characteristics of microwave beam-plasma devices (plasma TWT), definition of an opportunity of their application in communication systems and communication network, and also in the microwave technologies.

Researches were carried out in the following basic directions:

- Studying of systems of formation and transportation of intensive electron beams in the gas-plasma environment;
- Research of beam-plasma interactions in the transit channel of the hybrid resonance systems ;
- Research of plasma influence on electrodynamic and dispersion characteristics of slow wave structures (SWS);

* Research of the basic characteristics of plasma TWT models (amplitude-dynamic characteristics, amplitude-frequency characteristics, noise characteristics, out-of-band radiation etc.).

Prospects of the further development of scientific researches in the field of plasma electronics are connected with the scientific and technical results received on the given stage of the Project. High parameters of the studied plasma TWT breadboard models look attractive for their application in communication systems and communication network, in powerful microwave discharge technologies. For development of industrial samples and their batch production it is necessary to continue scientific researches in this field for the decision of physical, technical and technological problems of microwave electronics and microwave powerful beam-plasma devices.

**References:**

1.1. M.A. Zavjalov, L.A. Mitin,V.I. Perevodchikov et al. IEEE Transactions on Plasma Science, Vol. 22, No. 5, PP. 600-607, 1994.

1.2. G. Nusinovich, Yu. Carmel, T. Antonsen et al. IEEE Transactions on Plasma Science, Vol. 26, No. 3, PP. 628-645, 1998.

## II. Performance of scientific and technical works under the project

According to the Work Plan of the Project the executed works were submitted in quarterly reports, and also in the annual report. The most important scientific and technical results are given in sections of the present Final Report.

1. In the first quarter the following works are executed:

1.1. Analytical calculations of key parameters of models of a plasma traveling tube (plasma TWT) based on slow wave structure (SWS) such as chains of coupled cavities (CCC) with plasma filling of the transit channel are carried out.

For designing of plasma TWT models it was necessary to determine the basic characteristics:

a) parameters of slow wave structure (SWS);

b) parameters of an electron beam (a current, electron energy, plasma concentration) and technical requirements to an electronic gun and to the cathode unit;

c) pressure of working gas and the requirement to the gas-dynamic system of plasma TWT;

d) beam plasma parameters (plasma concentration, electronic temperature) in the CCC transit channel, created by an electron beam due to ionization of working gas and development of beam-plasma discharge (BPD);

e) magnetic field and technical requirements to the solenoid.

1.2. At realization of researches detailed modelling of slow wave electrodynamic system (SWS) with use of modern computer programs was executed. For the given frequency range the geometry of structure and its dispersion characteristic are determined.

1.3. With the help of mathematical modelling the electron-optical system (EOS) of electron guns intended for formation and transportation of an intensive beam in narrow extended channel (CCC) in a magnetic field is designed.

1.4. The experimental methods and techniques are developed and the test stand for adjustment and cold tests of CCC models is built.

1.5. The technique of research of plasma influence on CCC dispersion characteristics is offered and the model of the experimental stand for realization of "warm" tests of the hybrid slow wave systems (SWS) is created.

1.6. The technique of researches of EOS characteristics and electron beam transportation systems are developed. The experimental stand for realization of the given tests is made.

1.7. The documentation on electron gun models and slow wave structures of plasma TWT are developed.

1.8. Model samples of guns and slow wave structures of CCC are made.

2. The following completed stages of the work in the second quarter should be mentioned:

2.1. The hybrid slow wave structure (SWS) for a plasma TWT is developed.

2.2. The input matching device for simplification of SWS manufacturing technology is developed.

2.3. The model of matching transformer is made and researches of a standing wave ratio from voltage and frequency are carried out.

2.4. On the basis of calculations the required "canned" window was designed. Calculations have confirmed, that the relative band of working frequencies of the designed "canned" window is at a level of 35 %.

2.5. Within the given framework the calculations of dynamic characteristics of slow wave structures (SWS) are executed. Calculation of optimized slow wave structure was executed in an automatic mode with use of mathematical optimization methods on the basis of modern software complexes.

2.6. The prototype sample of the device is made. The assembled and soldered high-frequency part of the device has passed "cold" tests and adjustment at the special stand. By results of these tests the working documentation was updated.

3. In the third quarter the following works are executed:

3.1. Research of systems of formation and transportation of an electron beam in the breadboard model of the device in conditions of intensive beam-plasma interaction is carried out. Parameters of an electron beam satisfies the requirements of powerful plasma TWT.

3.2. The analysis of electron beam conditions in a breadboard model device is given at various pressure of working gas (hydrogen): “quasi neutral” beam, a three-component "plasma" beam, a mode of the beam-plasma discharge. The optimum pressure of working gas in plasma TWT is determined.

3.3. Calculation and research of the hybrid slow wave system is carried out, dispersion and impedance characteristics are obtained, the estimation of required parameters of a beam plasma is given.

3.4. With the help of the technique developed in VEI, "warm" tests of the hybrid electrodynamic structures are carried out which results allow to correct engineering calculations and design of plasma TWT.

3.5. Experimental researches of electron gun parameters, systems of magnetic control of an electron beam, processes of plasma generation and its parameters are carried out at the special test bed equipped with the necessary electrotechnical and physical diagnostic equipment.

4. In the fourth quarter works in the following directions are continued:

4.1. Research of microwave parameters of breadboard plasma TWT models, including amplitude-frequency and amplitude-dynamic characteristics, in vacuum and plasma modes is carried out on the experimental stand.

4.2. The analysis of parameters of the diagnostic microwave equipment for measurement of own noise of devices is carried out, methodical questions for realization of the given tests are solved.

4.3. Research of own noise of a breadboard plasma TWT model at absence of microwave oscillations at the input for various modes of operation of the microwave device is carried out.

4.4. The analysis of results of researches is carried out and the present annual report under the project is prepared.

It is possible to note the following basic scientific and technical results received during annual work on the Project:

1. Influence of plasma on electromagnetic properties of slow wave structure such as a chain of coupled cavities (CCC) was determined;

2.Calculation of dynamic characteristics of slow wave structures of CCC was executed;

3.The equipment, techniques are developed, results of experimental researches of characteristics of plasma TWT breadboard models is made, the prototype of plasma TWT have been developed;

4.Own noise of beam-plasma microwave amplifiers was measured.

- The basic scientific and technical results received under the Project 2347p within 4 quarters can be submitted as the following basic sections:

1. Influence of plasma on electro magnetic properties of slow wave structure (SWS) of type chain of coupled-cavity resonators (CCC).

In the course of these researches new method of experimental investigation of the CCC structure loaded with plasma was proposed and realized with use independent gas discharge plasma source with variable parameters. The results of “warm” tests of the hybrid slow wave structure (SWS) can be introduced in the system of engineering calculations and designing of plasma TWT.

2. Calculations of electro dynamic characteristics of slow wave structures of the chain couple cavity systems were carried out with use of the software complex of three dimensional program ISFELD3D. This program complex allowed to carry out calculations on matching of SWS

structures with expanded frequency band with regular energy transmission lines. With help of special calculation methods for coaxial and wave guide devices the construction of wide-band matching transformer was designed providing SWS frequency band up to 30-35%. Analysis of two-sectional SWS with optimization of resonators number in input and output sections and also in the coupled section was done with help of "VEGA" program.

2. Special equipment and experimental methods, experimental researches of characteristics of plasma TWT prototypes.

Diagnostic apparatus of universal experimental stand for investigation of microwave characteristics of designed and manufactured plasma TWT prototypes is described. Dependence of output power of electromagnetic radiation on hydrogen pressure is presented, which characterized transition to plasma operation mode with duplicate of electron efficiency. Amplitude-frequency and dynamic characteristics of broadband plasma TWT models are investigated. Plasma operation mode showed increase of output microwave power to 20 kW along with broadband frequency of TWT prototypes.

3.Measurement of self noise of broadband models of microwave beam-plasma amplifiers.

For research of own noise characteristics of breadboard models of plasma TWT methods of measurements are chosen and special measuring installations are created on the basis of original devices and circuitry design (a panoramic measuring instrument of spectral power density, the gyromagnetic filter with frequency matching etc.)

Researches of self-noise characteristics of plasma TWT model at absence of input microwave signal showed that there is a complex oscillation spectrum at the amplifier output, created by parasitic oscillations (frequency-modulated and quazimonochromatic oscillations) and narrow-band and wide-band stochastic (noise) oscillations of TWT selfnoise in the studied frequency band at the level below 45 dB.

- In the fifth quarter the following works were carried out:

5.1. Experimental researches of beam-plasma parameters created by electron beam due to ionization of working gas in the transit channel of plasma TWT are continued. Optimal parameters values are estimated for TWT plasma operation mode.

The estimation of threshold value of working gas pressure is given for transition to collective beam-plasma interactions ($\sim 7 \cdot 10^{-4}$ mm Hg). Probe measurements of plasma parameters in the CCC transit channel on experimental model of plasma TWT are fulfilled. The substantiation of application of probe techniques is given in conditions of intensive electron oscillations and presence of strong magnetic field. Value of electronic temperature in a beam-plasma interaction of ~15-20

eV is obtained which corresponds to calculations on non-linear mathematical model, and also to common estimations and to experimental results. Probe measurements fulfilled at electron beam energy of 20 KeV, beam current 2.5 A, hydrogen pressure $\sim 2\cdot 10^{-3}$ mm Hg, showed that plasma concentration in the field of probe reaches value of $1\cdot 10^{12}$ $cm^{-3}$ . The ratio of gas ionization speed by plasma electrons to speed of gas ionization by fast beam electrons is received, the estimation of ambipolar plasma potential is given.

5.2. Experimental measurements of gas-dynamic processes in a pulse operation mode in the sealed-off device are carried out, their analysis is made with the taking into account gas desorbtion from a surface of a collector under action of electronic bombardment, and gas photo-desorbtion from elements of a transit way under influence of radiation at development of the beam-plasma discharge, effect of "stiffness" at transportation of an electron beam, and action of incorporated evacuated means inside the tube.

The carried out researches have allowed to optimize the gas-dynamic system of the device and as to specify conditions of beam plasma generation for realization of plasma operation mode of TWT on the basis of the hybrid electrodynamic structure (CCC). Special measurements have confirmed, that results of calculations of operation modes of a breadboard plasma TWT model and maximal efficiency of microwave radiation corresponds to optimum values of beam plasma concentration.

5.3. Research of the coordination of a breadboard plasma TWT model is carried out from an input and an output in various modes with application of various techniques and equipments. The standard technique with use of panoramic measuring instrument KSVN (VSWR) and attenuation is applied in a "cold" operation mode, that is with an idle breadboard plasma TWT model. Results of research of the coordination on an input at short circuit on an output of the TWT model have shown, that in a working frequency band the influence of loading short circuit is absent. It testifies that the absorbing elements located inside the electro-dynamic structure play role of loading for the input electromagnetic flux.

Researches of the coordination of a breadboard plasma TWT model on an input in a "hot" operation mode (the rated operation mode of amplification) are carried out also. Measurements are carried out with the help of microwave power instruments connected to directed couplers in an entrance path of a breadboard plasma TWT model. The couplers were back-to-back connected for measurement of the incident and reflected power. The analysis of results of the given measurements in comparison with standard "cold" tests is given.

5.4. Researches "low-frequency" noise and out-of-band oscillations of a breadboard plasma TWT model (in a frequency band which is lower than the working frequency band, and also in the field of ionic - plasma, magnetic-sound oscillations with a range of hundred kHz - tens MHz) are

realized. Preliminary results testify on a complex nature of researched effects, their dependence on a magnetic field, on working gas pressure, parameters of an electron beam and on a level of amplified signals. The given researches can be continued within the framework of prolongation of the given Project.

5.5. Researches of a multi-frequency operation mode of a breadboard plasma TWT model which are actual for definition of an opportunity of application of microwave plasma devices in telecommunication and communication systems are carried out. The computer program (special software) allowing to calculate power of combination components of the first (the basic components), the third and fourth orders on the basis of the given powers and frequencies of two input signals.

For realization of experimental researches the measuring installation consisting of two driving microwave generators, the preliminary amplifier, the filter, a wattmeter and spectrum analyzer was created. Signals from driving generators are applied on an input of a breadboard plasma TWT model through the preliminary amplifier and the filter. The assignment of the filter - to suppress combinational components of the total signal spectrum formed in the preliminary amplifier. The wattmeter was used for measurement of total power of signals, spectrum analyzer - for measurement of frequencies and relative levels of combinational components.

Calculations were made and experiment with two signals of the same power with a difference of frequencies 70 MHz are carried out.

The results of experimental measurements having satisfactory concurrence with the calculated data, have shown, that combinational components of the third order have a level of –26 -24 dB comparing the basic components of a signal, and combinational components of the fourth order have the corresponding level of –37 -36 dB.

- The given Final Report contains materials of the Quarterly Reports and of the Annual Report, and it also contains the results of additional researches in the following directions:

- Electron-optical systems of guns for plasma TWT;
- Experimental researches of microwave characteristics of the Hybrid Beam-Plasma Electro-Dynamic Systems.
- Experimental research of two-frequency operation mode of plasma TWT model.
- Research of out-of-band oscillation of plasma TWT models.
- Analysis of possible application of beam-plasma devices in radio-technical communication information systems,
- Microwave heating of materials and microwave discharge technology.

## III. Electron-optical systems of electron guns for perspective microwave beam-plasma devices

Creation of the powerful broadband frequency microwave amplifier has demanded the solution of some physics-technical problems: development of system engineering of formation and transportation of an electronic beam (20 keV, ~ 3A) in the narrow extended transit channel of the slow wave structure (SWS) (diameter of 1,2 cm; length ~ 40 cm), filled with plasma; gas-dynamic systems of the sealed-off device, providing adjustment of working gas pressure in required limits ($10^{-6}$ - $10^{-3}$ Torr) with the help of hydrogen generators, and also providing vacuum difference between the plasma electro-dynamic system and electron-optic system of the electron gun; output systems of amplified microwave power.

In the plasma TWT electron beam is transmitted in the transit channel, placed in the longitudinal magnetic field with flux $B_{zm}$ = 0,25 T. In the CCC transit channel plasma is generated with concentration to $10^{12}$ $cm^{-3}$ and electron temperature ~15—20 eV as result of gas ionization by electron beam and beam-plasma interaction. For plasma operation mode the following relations should be valid:

$$\omega_b^2 << \omega^2 < \omega_e^2 < \omega_{eh}^2,$$

where $\omega_b$ — electron frequency of electron beam;

$\omega$ — working frequency;

$\omega_e$ — electron plasma frequency;

$\omega_{eh}$ — electron cyclotron frequency.

In the working model of the microwave beam-plasma microwave device (plasma TWT) electron beam is emitted from the flat thermoionic cathode with diameter of 1 cm. Beam parameters are coordinated with calculation results of electro-dynamic structure. Magnetic field in the cathode flat plane is of 0,3—0,5 of maximum value. Design computing of the electron-optical system was carried out with help of software ERA, ESTAMP, ERA-RINOTS.

In an operating conditions a "plasma beam" condition is realized in the system at which an electron beam with electron concentration $n_b = 3*10^9$ $cm^{-3}$ is transported in the dense plasma $n_e = 10^2 n_b$ generated by an electron beam at evolution of the beam-plasma discharge.

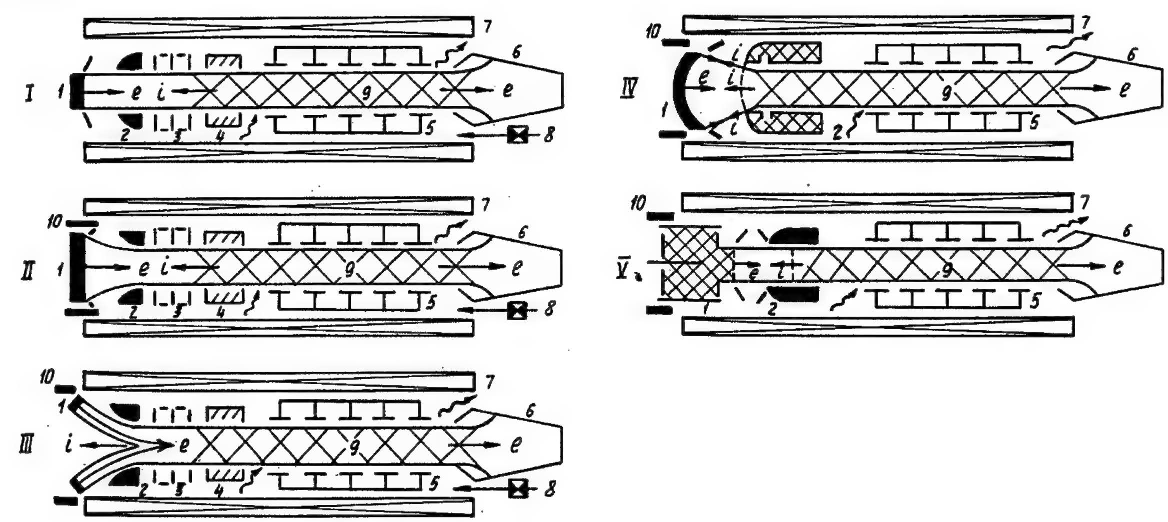
For decrease of influence of beam-plasma processes in the hybrid electrodynamic structure on the gun electron-optical system (EOS) work, the two given systems, as it is noted above, are divided with the built-in evacuation system. It consists from the sorption pump and the magneto-discharge

pump working in a field of solenoid, which electrodes form an ionic trap for protection the thermoionic cathode from ionic bombardment.

Because of complex operation modes of the device the $LaB_6$-cathodes (1650 °C, heating power 120W, efficiency ~ 25 mA/W) are used in the models , the last of which is now the basic element of electron guns.

For the beam-plasma amplifier with the increased microwave power a new electron-optical system (EOS) was developed with an electron gun power of 300 kW (30 kV, 10 A). The increased beam current up to 10 A has caused a choice of the $LaB_6$-cathode 1.5 cm diameter, with this there were rigid restrictions on diameter of transmitted electron beam (0.8-0.9 cm) transported for length of ~ 50 cm at the minimal deflections of border.

Optimization of the design is executed under the program of paraxial synthesis with consideration of ionic background compensating action and a magnetic field of the solenoid, modified on an initial part of electron beam distribution by means of the magnetic screen. Definition of the form and an arrangement of the magnetic screen in relation to the solenoid and to the cathode of an electron gun were calculated under software program SPLAV, and influence of the technological form of electrodes on geometry of a beam - under the program of trajectory analysis - ERA.




1 – cathode, 2 – anode, 3 – magnetic-discharge pump, 4 – sorption Ti-pump, 5 – electrodynamic slow wave structure (CC SWS), 6 – collector, 7 – solenoid, 8 – hydrogen generator, 9 – plasma-beam, 10 – magnetic screen.

I. EOS with thernionic cathode (cathode diameter is approximately equal transit channel diameter).

II. EOS with electron beam compression.

III. EOS with unbroken or multi-jet ion-protected ring cathode.

IV. Bipolar EOS with plasma anode. 2 – anode – ring gas-discharge source of anode plasma.

V. EOS with plasma cathode. 1 – cathode – gas-discharge source of cathode plasma, acting at working gas pressure in tube.

Fig.3.1.

The Fig. 3.1 illustrates various types of EOS design of guns and other elements of microwave beam-plasma devices, starting from already realized devices (I, II), being developed now (III), and also perspective models (IV, V). Input and output of electromagnetic oscillations are shown with wavy arrows. In designs I and II the flat $LaB_6$-cathodes are used forming axial-symmetric electron beams, transmitted in the plasma transit channel of the hybrid electrodynamic structures at working gas pressure (hydrogen) of $\sim 7*10^{-4} \div 1*10^{-3}$ Torr. In designs I - III the gas-dynamic system of sealed-off device is used, including controlled hydrogen generators and evacuation (sorbtion and magnetic-discharge pumps) and such design already became "classical".

The design III offers variants of ionic-protected optics with the ring cathode or optics with single-layered ring multi-beam structure which theoretical aspects are discussed below.

In the given design use of economic low-temperature oxide cathodes and W-Ba-cathodes with the long service life is possible. Besides, in a case of multi-beam systems, the device will continue to operate even if one or several "microcathodes" fail.

It is necessary to note, that introduction of the register (registrator) of an ionic current, which value is directly connected to the beam plasma parameters in the hybrid structure, which parameters determine output microwave characteristics, can be used in a system of control and stabilization of a plasma operation mode of the device.

Perspective designs IV and V, at first sight, can to seem "exotic", but the offered design decisions of electron guns already have passed theoretical and experimental studies on models.

In work 3.1 the bipolar electron-optical systems of guns with thermo-ionic cathode and with the plasma anode (see design IV) are analyzed. Experimental researches have shown an opportunity of practical realization of high-purveyance EOS of guns for quasi-stationary and stationary operation modes.

Bipolar EOS, "adjusted" with the help of independently controlled sources of plasma, can find application for plasma electronics devices with beam injection in the plasma transit channel of the hybrid electrodynamic slow wave structures (SWS). In the similar devices the plasma anode (an independent gas discharge source of anode plasma) is a matching element between an area of intensive beam-plasma interaction and EOS area of a gun. Application of high-purveyance bipolar EOS in TWT will raise their efficiency due to increase of Piers parameter.

Creation plasma-anode bipolar EOS with thermo-ionic cathode, heated up in regular intervals by ionic stream (flux) distributed on the cathode surface, can result in significant simplification of a design of cathode units of guns, and also of high-voltage power supplies.

In work 3.1 results of test of an electron gun (executed with the design similar to design IV) with plasma-anode EOS and with the cathode heated up with ions are presented. At high voltage applied to the spherical $LaB_6$-cathode of 1,8 cm in diameter and achievement of necessary ionic

beam power adjusted by discharge current of a ring plasma source having ground potential, the cathode is warmed up to temperature, sufficient for thermo-ionic emission. Tests of a gun were carried out at voltage up to 25 kV. Realization of the proposed model (see design IV), certainly, will demand to proceed theoretical analysis of bipolar EOS with injection of an electron beam in the plasma transit channel in a magnetic field.

At the same time, the idea of creation the model of "realistic plasma" microwave device which includes the plasma cathode and the bipolar electron-optical system with the plasma anode (see design V) is attractive. In such model generation of plasma in a gas-discharge source of the plasma cathode and in the field of hybrid plasma electrodynamic system (area of the beam-plasma discharge), forming also the plasma anode, can take place at the same working gas pressure in all system ($\sim 7x10^{-3} \div 1x10^{-3}$ Torr).

Attempt of development of the plasma cathode with "consumtionless" discharge source with cold electrodes was already undertaken. [3.1]. In this work results of the researches directed on realization of high-current low-voltage mode of glow discharge at pressure $\sim 10^{-3}$ Torr in a system of type “inverted magnetron” are presented. There is also results of development of electron injector with the plasma cathode providing an electron beam of millisecond duration with cross section about 1 $cm^2$, a current up to 3 A at energy of particles of 20 keV.

The choice of a way of plasma generation was caused with high efficiency of gas ionization in the crossed electric and magnetic fields, simplicity of initiation of such discharge, and also an opportunity of use of the solenoid magnetic field. Magnetron cell is formed by the cylindrical cathode and the rod tungsten anode (see design V).

As a result of the carried out researches conditions of ignition and stable burning of the pulse and continuous glow discharge were determined in the system " inverted magnetron " without gas pumping at low pressure and discharge currents up to 10 A and the factors promoting increase of efficiency of electrons extraction are revealed. The opportunity of creation of electron injector with the plasma cathode forming an electron beam with required parameters is shown.

The given model of the device (see design V) can have doubtless advantages in comparison with the existing realized devices. There are following advantages: single initial gas filling (for example, inert gas) of the sealed-off device corresponding to working pressure, at absence of filling gas systems and evacuation systems, having the limited resource of work; presence of the plasma cathode, not critical to ionic bombardment, instead of thermoionic cathode; an opportunity of pulse-frequency modulation of a current of an electron beam and of output power of electromagnetic radiation due to control of a gas-discharge source of the plasma cathode [3.1].

In work [3.2] questions of generation and formation of bipolar electron beams are discussed.

The problem of formation of bipolar beams with counter-movement of electrons and ions has

a rich history, starting from the space-charge Langmuir task for the flat diode to practical application of electron guns and electron injectors with bipolar electron-ion-optical systems with the plasma anode.

There are known theoretical and experimental researches of spherical, cylindrical and other bipolar systems with different electron emitters and with use of various types of plasma anodes. If earlier plasma processes in the field of formation and the transportations of electron beams influencing on work of guns, were considered as accompanying effects (basically- negative), now these effects start to be used for creation of electron beams with the high parameters, inaccessible for traditional unipolar electron-optical systems.

Electron guns with bipolar streams both stationary, and pulse modes in which thermoionic electron emitters, plasma emitters, explosion-type emitters and secondary-emission emitters are used, start to find practical application.

The bipolar systems have special value with development of plasma electronic devices. It can be mentioned as example the development of a plasma TWT which transit channel is filled by the plasma generated by a electron beam itself.

Questions of application of magnetron-injector guns (MIG) in beam-plasma microwave devices are discussed in this work. The mathematical simulation of electron-optical systems (EOS) and proposals on development of electronics optics according the design line "synthesis - technological electrodes - the analysis " with application of the geometrical theory of dense electron beams are presented.

Progress of plasma TWT development in area of lager powers demands creation of electron guns forming non-relativistic electron beams of power to 1 MW in quasi-stationary operation mode (pulse duration $\geq$ 1 ms). Thus the basic conditions of transportation of the electron beam, determined by the parameters of the hybrid beam-plasma microwave electrodynamic systems, should correspond to parameters of developed plasma TWT models.

In work [3.3] application of electron gun of magnetron-injector type for plasma TWT is offered. There are known designs of high-purveyance magnetron guns forming tubular electron beams for vacuum microwave devices of Cherenkov's type (klystrons, TWT).

The direction of work on application of magnetron injectors, forming ring electron beams with spiral trajectories (screw spiral electron beams) for masers on a cyclotron resonance (gyrotrons) is widely advanced also.

The opportunity of application of powerful high-purveyance magnetron guns for non-relativistic microwave beam-plasma devices of Cherenkov's type (plasma TWT) requires a number of specific requirements to their characteristics.

Volumetric waves in the hybrid plasma structure have the maximal value of longitudinal

components of an electric field on an axis of a wave guide in comparing with the usual vacuum slow wave structures (SWS) in which effective interaction of an electron beam with a wave field occurs only in an immediate proximity from the structure, that at significant thickness of a beam results in participation in interaction only its superficial part.

Therefore the magnetron gun should form a continuous cylindrical electro beam with sufficient uniformity of current density distribution along its sections.

In difference from usual magnetron guns it, obviously, demands not only substantial growth of emitting surface of the cone cathode, but also demands to cover a spherical part of the cathode with the emitting material.

As Cherenkov's mechanism of radiation assumes presence basically of longitudinal component of electron speed, magnetron emitting device should form a beam with a small fluctuation (pulsation) level (anyway the pulsation amplitude should not exceed 10-15 % from the maximal radius of a beam in the transit channel). For providing a long service life of the cathode the emitting current density should not exceed 6 A/cm$^2$, and current density distribution along from the cathode envelope should be close enough to uniform.

At last, it is necessary to provide dielectric strength of a gun. It is considered, that for this purpose the "cold" electric field on the cathode should not exceed 6 kV/mm. We should note also, that magnetron emitting device should work in an operation mode with current restriction by a space charge. It is easy to see, that the specified requirements, in general are inconsistent and considerably differ from accepted requirements for magnetron emitting devices for gyrotrons.

It makes impossible direct application the well advanced adiabatic magnetron emitting gyratrons theory for estimation of magnetrons parameters and results in necessity of development a new approaches, adequate to a task in view of beam-plasma magnetron devices.

Results of theoretical calculation of two variants (diode and triode) of magnetron guns with the following parameters are given:

accelerating voltage — $U_0 = 30$ kV:

beam current — $I \approx 20$ A;

beam radius is the interaction space — $R_{max} = 5$ mm;

amplitude of focusing magnetic field— $B_0 = 2.5$ kGs;

cathode current density — $j_K \leq 6$ A/cm$^2$;

"cold" electric field on the cathode — $E_K < 6$ kV/mm;

pulsations of a flux top border , not more — $\Delta R_0/R_{max} \approx 15\%$

Calculation and optimization of the electrodes form and electric operation mode of an electron gun were carried out on base of the trajectory analysis under the program the EPOS. The

current restriction mode by a space charge was considered. As calculations have shown, for maintenance of a moderate pulsation level the cathode of a gun has to be placed in the strong enough magnetic field about $B_o/2$. In the diode option of a gun, according to the calculation data, the radius of the anode repeatedly exceeds radius of the cathode and a "cold" field on the cathode can be estimated under elementary formula $E_k = U_O/R_K$.

Assuming an average radius of the cathode $R_k \approx 5$ mm, we receive $E_k \approx 6$ kV/mm, that is close to a maximum permissible value. The trajectory analysis shows, that on a spherical part of the cathode the electric field reaches value 5,5 - 6,5 kV/mm. The larger value of a field results in excessively high peak current density in a restriction current mode byy a space charge – $j_k \approx$ 10-15 A/mm$^2$, and difference of current on the emitter can reach three times. Heterogeneity of current distribution on the cross-section in the transit channel is great also. Pulsation of trajectories is about 20 % from $R_{max}$ and it exceeds the admissible limit a little.

Therefore it was considered further the triode option of a gun with anode voltage $U_a = 15$ kV.

Optimization of the form of electrodes of a gun in this case has allowed to provide an electron beam with a current 16,7 A, at pulsation level about 7 % and close enough to uniform distribution of current density at the cathode. In this case $j_k = 6$ A/mm$^2$. The given system already allows to form a beam with power of 500 kW with acceptable parameters. The electric field on the cathode does not exceed 3,6 kV/mm. We shall note, that according to the data of the trajectory analysis, parameters of a beam a little vary at increase of voltage at the second anode up to 40 kV (beam power is of 670 kW).

**References:**

3.1 M.A. Zavjalov, V.I. Perevodchikov, V.A. Syrovoy. Proceedings of SPIE Vol. 4187. 2000. pp. 138-145.

3.2 M.A. Zavjalov, V.A. Syrovoy. Bipolar beams. Proceedings of SPIE, 2004, to be published.

3.3 M.A. Zavjalov, V.A. Syrovoy, V.N. Manuilov, E.A. Soluyanova. Applied Physics, № 3, 2002, pp. 74-79.

# IV. Calculation of dynamic characteristics of the hybrid slow wave structures such as SWS CCC

## 4.1. Research and development of calculation methods of matching devices for coordination of SWS with the regular wave guides

One of the main goals with development of the wide-band slow wave structures (SWS) is the problem of creation the input and output devices providing matching SWS with the regular wave-guides.

Two-dimensional software programs such as "NEVA" and "YAUZA" used for SWS calculation are not suitable for this purposes, as even at calculation of regular SWS parts it does not provide high accuracy of the account.

Therefore essentially new three-dimensional calculation modules of dynamic characteristics and electronic parameters of SWS were developed. The complex of programs ISFEL3D was used as a base program environment. [4.1].

The complex of programs ISFEL3D of version 6.0 is intended for modeling by a method of final elements the electromagnetic fields in frequency range in objects of the any form. ISFEL3D is a reliable means for the decision of the following problems:

1. Program complex ISFELD3D allows to carry out the spectral analysis of the closed structures, including high-frequency resonators of microwave devices and accelerators of the charged particles.
2. It allows to carry out calculation of dispersion parameters of microwave structures with the wave guide input / output of the energy, excited by a wave of the certain type in the given frequency range (vacuum-tight windows, wave-guide devices and transitions between transfer links of various cross sections, resonators etc.).

This complex of programs is easy for using for calculation of several modes of oscillations (the number of oscillation modes is not limited), and also for allocation of a separate mode of oscillations (it is not necessary the basic oscillation), the nearest to the given frequency. ISFEL3D provides the analysis of the structures filled with any non-uniform isotropous lost-free magneto-dielectric.

ISFEL3D works in operational environment Windows 98/2000/NT/ME/XP. It gives users a flexible and effective platform for the decision of problems with help of rather cheap and powerful personal computers.

The complex of programs is based on the computation of Maxwell equations by a method of tangential final elements concerning a vector of an electric field [2.1]. The method is realized on the first order elements in the form of rectangular parallelepipeds which are formed by crossing of

coordinate planes in the Cartesian system of coordinates. Cells of a grid can have the variable sizes in all three coordinates. The specific configuration of final elements allows to enter simple, but exact, approximations of a field which considerably simplify numerical calculations. At the same time, the integrated nature of the used variational formulation simplifies the decision at step approximation of curvilinear surfaces. False decisions are effectively excluded by a special technique.

The realized procedure provides well organized resulting system of the algebraic equations that results in essential computing economy for solving the big problems and reduces probable cost of the decision.

Using the postprocessor of a program complex ISFEL3D, it is easily to find the important parameters, such as own quality factor, entrance resistance, wave resistance, communication impedance, intensity of fields, distribution of losses in a metal environment etc.

The interaction of the programs included in structure ISFEL3D 6.0 is shown in Fig.4.1. The entrance processor of the geometrical description of three-dimensional objects RDV3D generates a network of final elements and quickly and effectively allows the user to create three-dimensional model of microwave structure which should be analysed. The resulting data containing the characteristics of a filling material, are used in the module of the decision of problems(tasks) on own values MES3D, and also in the module of the analysis of dispersion parameters MES3DS. Two last programs generate, in turn, the additional data used in postprocessor PAC3D for viewing and the analysis of results of the decision. During the work the program complex ISFEL3D creates some files for each project. File name extensions 'IN' and 'OUT' are used for the text files containing accordingly the input and output information. These files are intended for the user. Files with extension 'RES' include the data in a not formatted mode and serve as input files for components of a program complex ISFEL3D.

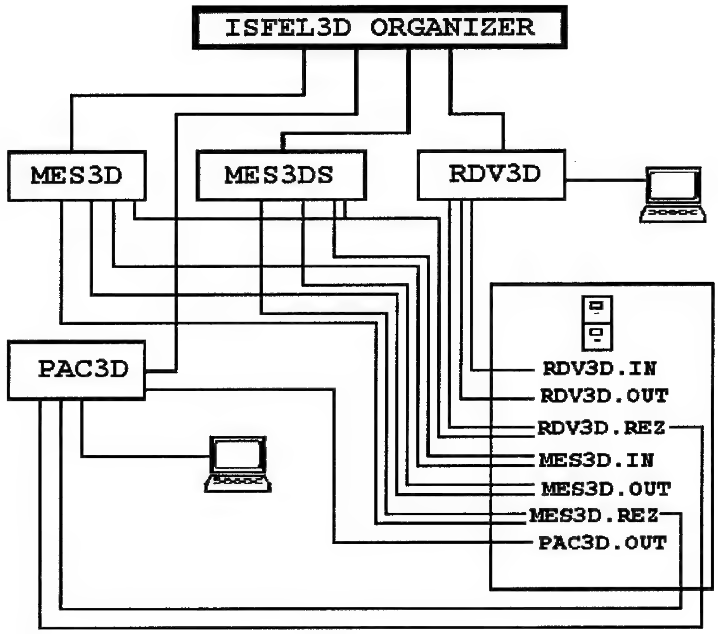



Fig. 4.1. Interaction of programs in ISFEL3D software complex

The developed complex of programs is a base stage for creation of beam-plasma TWT SWS with the expanded frequency band. The complex of the developed programs surpasses foreign analogues in many characteristics and allows to reduce considerably financial and labour expenses in the course of design of microwave devices.

During work the idea of a new design of the broadband matching transformer as the coaxial – wave guide adapter ( Fig. 4.2) was offered.

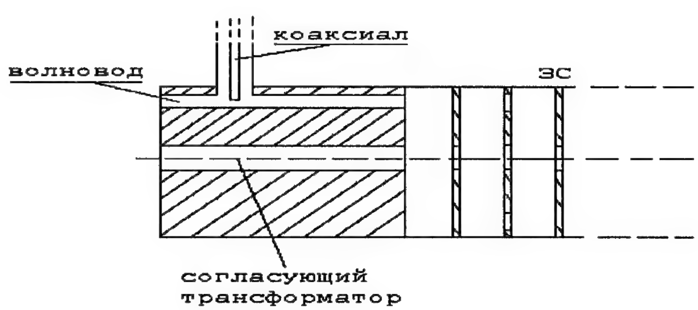



Fig. 4.2. The schematic view of matching transformer as the coaxial-wave guide adapter

The modernized complex of programs ISFEL3D has allowed to carry out calculations of SWS matching transformer of the device as the bent piece of a wave guide according to the drawing shown in fig. 4.3.

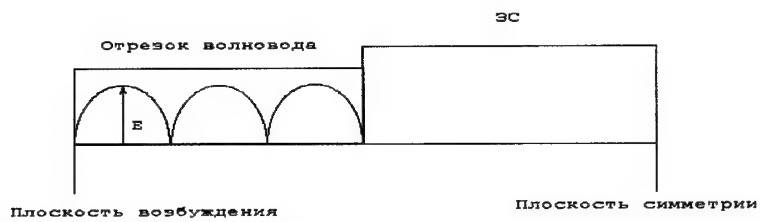



Fig. 4.3. Connection of SWS with a part of wave guide.

The beginning of a wave guide corresponds to an excitation plane, then SWS goes, terminating in a plane of symmetry. As far as SWS has a plane of symmetry relatively to distribution of a running wave (the input and an output are identical) in this case it is just enough to carry out only two calculations on a standing wave: in a plane of symmetry the idling conditions (IC) is set and in a plane of symmetry the short circuit mode (SC) is set.. Thus in each mode along the structure length and in a wave guide the standing wave is formed. On the certain frequencies in an excitation plane the node of an electric field $\vec{E}$ can arise (both in IC mode and in SC mode) These frequency points recalculation at change of a wave guide length increases calculation time. At an arrangement of an electric field node near to an excitation plane calculation time also is increased, the iterations number can increase from 1700-1800 at favorable node position up to 7000-8000.

After that electromagnetic fields on a running wave are calculated on a standing wave. The example of a picture of an electric field distribution on a running wave is shown in Fig. 4.4.

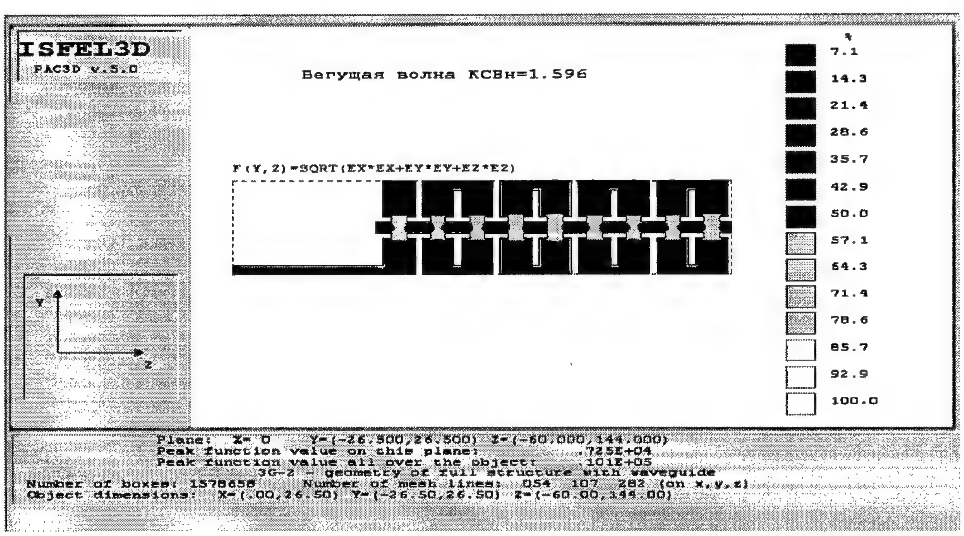



Fig. 4.4. An electric field distribution on a running wave in the system consisting of a piece of a bent wave guide and a half of SWS.

It is seen from Fig.4.4 that an electric field is uniform in a wave guide at good matching with SWS (f =2425 MHz; VSWR =1.596).

Calculated dependence of Voltage Standing Wave Ratio (VSWR) from SWS frequency of the device with the matching transformer made as the bent piece of a wave guide for two different SWS geometries is shown in Fig.4.5 (row 1 and row 2).

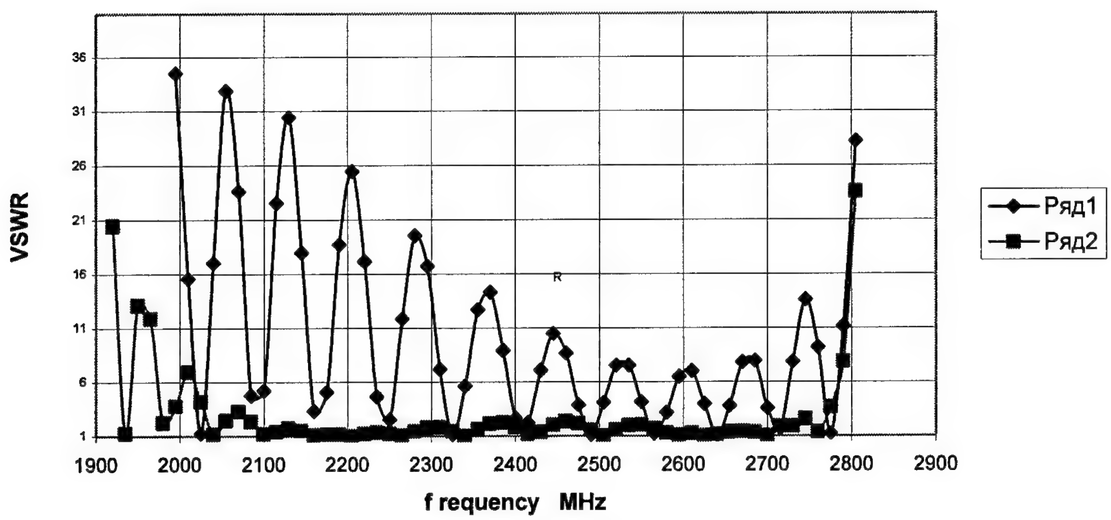



Fig. 4.5. Calculated dependence of Voltage Standing Wave Ratio from SWS frequency of the device with the matching transformer made as the bent piece of a wave guide.

The received results at SWS calculation for powerful wide band plasma TWT with the help of the modernized software program complex ISFEL3D have allowed to develop and to make the breadboard plasma TWT models for tests.

### 4.2. Calculation of electro dynamic characteristics of SWS.

Calculation and optimization of SWS geometrical sizes is carried out in an automatic mode with use of mathematical methods of optimization with the help of the calculation program of dispersion characteristics of slow way system " ISFEL3D ".

Results of calculation are given in Fig. 4.6.

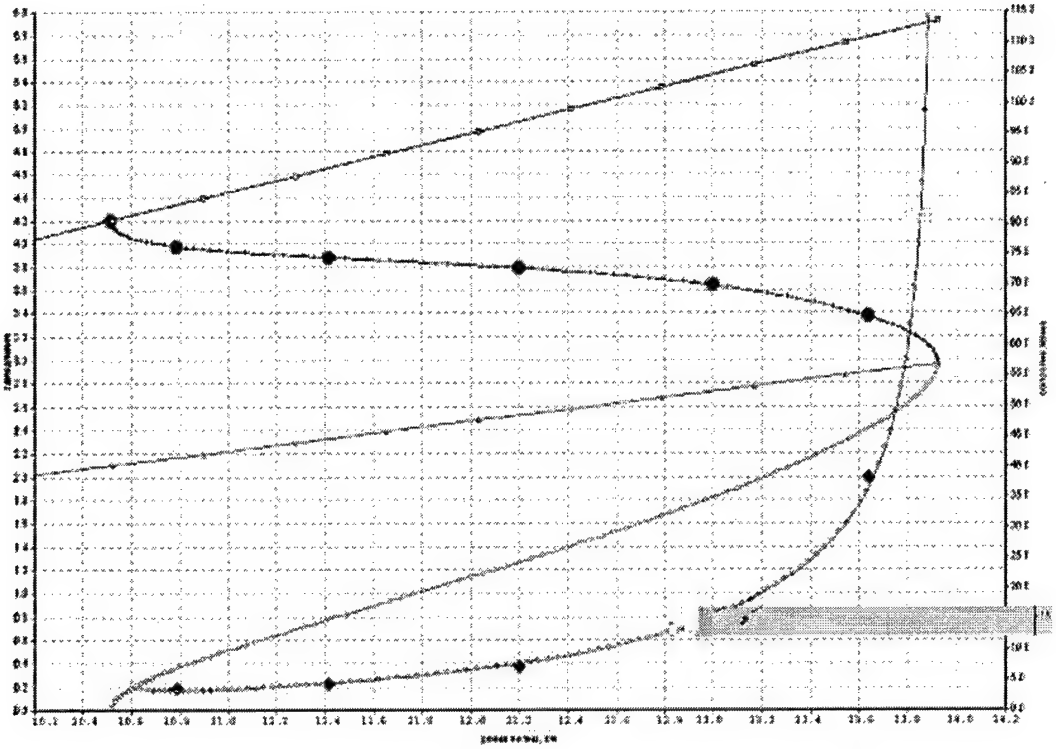


Fig. 4.6. Dispersion characteristics of SWS obtained with the help of «ISFEL3D» program.

The following parameters were used as criterion of optimization:

1. working frequency band;
2. maximum possible interaction impedance (coupling coefficient);
3. mistuning factor change in the working band interval from –1 to 2.

All the sizes of slow wave system except for radius of the transit channel were changed during calculation. As a result of the carried out optimization the slow wave system which sketch of a design is given in Fig. 4.7 was obtained.

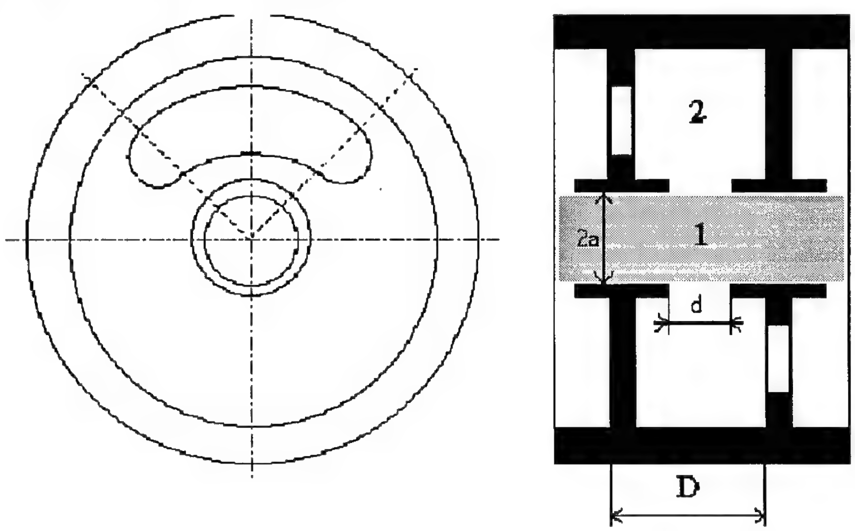



Fig. 4.7. Design of SWS elements.

It is seen from the received results, that the error in definition of coupling coefficient reaches 100 %, and an error in definition of long-wave border of a pass band is of 6 %. Coupling impedance of the chosen system is maximum for the given frequency band. Shift of the long-wave frequency border demands selection of a working voltage and a current of an electron beam during optimization of a structure of the device.

Optimization of structure of the device was carried out with the help of the program "VEGA" [2.2] in an interactive mode. The device was designed as the two-sectional TWT with the decoupling unit between sections on the basis of the chosen slow wave system such as CCC. Frequency coordination at an input and an output of the device was supported in all a working frequency band at level VSWR 1,5.

The following parameters are varied:

1. voltage and current in the given range;
2. resonators number in input and output sections and in the decoupling unit;
3. absorption factor in the decoupling unit.

As a result of the carried out optimization the following design of SWS was obtained (Fig. 4.8).

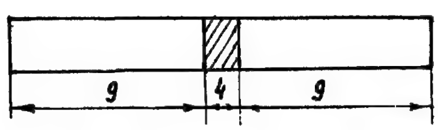



Fig. 4.8. Structural design of the optimized SWS.

Input and output sections contain 9 resonators, decoupling section contains 4 resonators. Working voltage is 22,6 kV, electron beam current is 3,5 A. Attenuation introduced by the decoupling section is submitted in Fig. 4.9. Results of calculation of output characteristics of the optimized device are submitted in Fig.4.10 and Fig. 4.11. Apparently from the received results the optimized device provides output power more than 15 kW at input power of 100-200 W in all the working range. Electronic efficiency is of 22-25 %, in a frequency band of 25-30 %.

The carried out analysis has shown, that the further increase of a working band can be obtained due to the account of plasma effects (high-frequency shift of a band by 5-10 %) at recalculation of the hybrid SWS with the modernized program " ISFEL3D 2002 ".

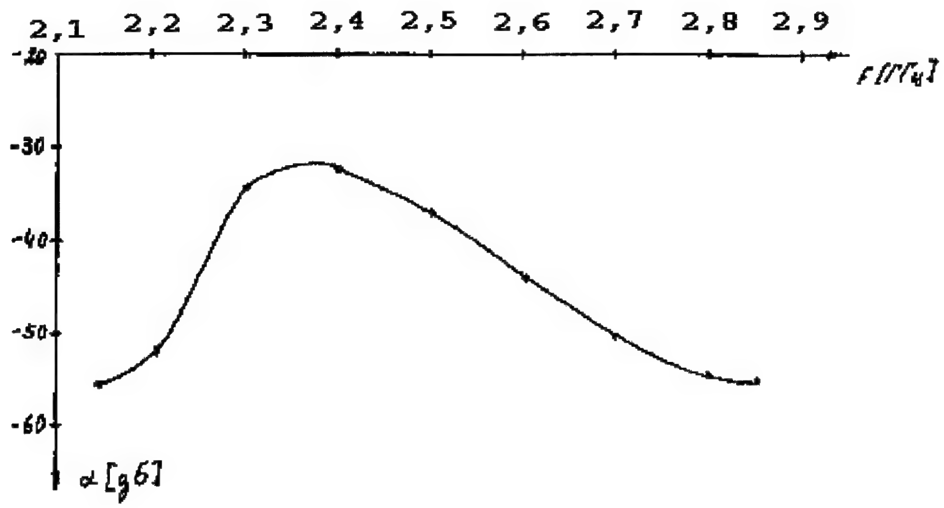



Fig. 4.9. Attenuation introduced with the decoupling section.

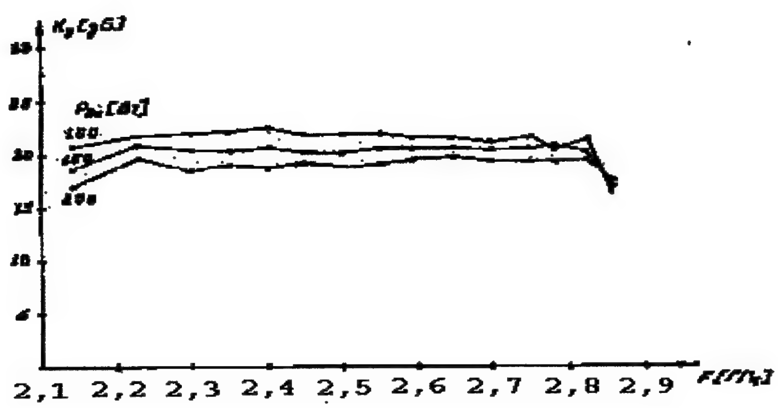



Fig. 4.10. Change of amplification factor in the working band

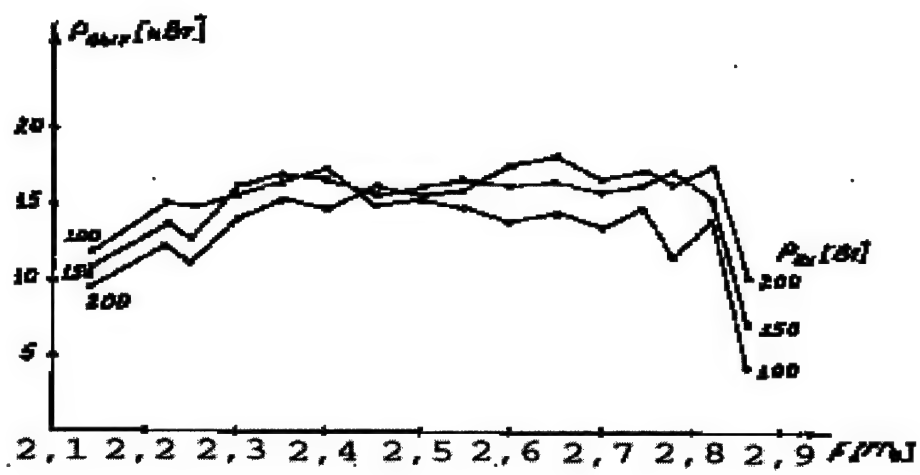



Fig. 4.11. Amplitude-frequency characteristic of SWS

The carried out works on calculation of dynamic characteristics of slow wave structures such as CCC have allowed to draw the following conclusions:

1.With help of the modernized complex of three-dimensional computation programs ISFEL3D calculations of the matched SWS with the expanded frequency band with regular energy transfer lines are made.

2.With the help of the developed design procedures for coaxial and wave guide devices the wide band matching transformer design was offered.

3. The analysis of two-section SWS in an interactive mode is carried out with the help of the program "VEGA". The optimum number of resonators at the input and at the output sections is determined.

**References:**

4.1. Silaev S.A. Application of the code ISFEL3D for three-dimensional structure calculations //Proc. Int. Univ. Conf. "Electronics and Radiophysics of Ultra-High Frequencies", St. Petersburg, 24-28 May 1999. - P. 407-410.

4.2. S. Mukhin. The Dissertation of Dr.Sci.Tech. degree. MIEM, Moscow, 2003. (In Russian).

# V. Plasma influence on the electromagnetic properties of the coupled-cavity slow wave structures

## 5.1. Electromagnetic properties of the slow wave structures.

Many characteristics of microwave plasma devices demand the further researches. One of the important problems is plasma influence on electromagnetic properties of the slow wave structure (SWS) such as a chain of connected resonators (coupled-cavity resonators - CCC). There are known researches of the radial non-uniform plasma generated by a special pulse source on the SWS structures, with use of the modified resonant method [5.1].

It is sufficient to indicate that there is a number of characteristics of these devices which should be addressed for further investigations. One of most important is plasma influence on the electromagnetic properties of CCC SWS. The results of radially nonuniform plasma column from pulse source effects on the electromagnetic characteristics of two different SWS's (rippled wall structure and CCC SWS), received by modified resonant cavity technique, are known [5.1].

In this report the electromagnetic characteristics of model of CC SWS similar to those used in are investigated. Resonant methods with shorted SWS are attractive for measuring the characteristics.

The research was performed in two steps. The first step was the cold test of spatially periodic structure (empty CC SWS). In the second step hybrid model based on CC SWS with special gas-discharge tube introduced into channel are investigated. The hybrid mode results from the coupling of the "vacuum" fields in the cavities with a plasma mode, which exists in a narrow drift channel. This test of plasma loaded CC SWS may be named "warm" test. Glow discharge in an inert gas was existed in 1 cm-diameter sealed glass tube. Schematic view of the measuring system is shown in Fig.5.1.

Some resonators with coupling splits was closed by shorting plates with a holes on the center. The influence of these holes on frequency band-width is small (less 0,5%). In this system was introduced two coupling loops. One of them excites microwave oscillations, the other gives signal after detector to P2-54 indicator.

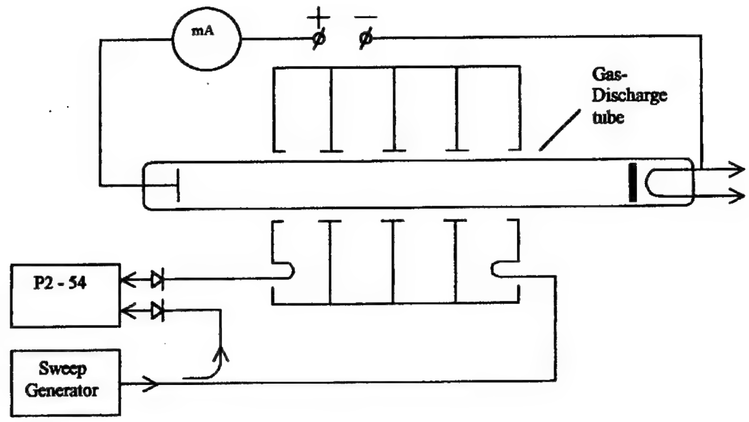



Fig.5.1. Schematic view of the measuring system

Previously, plasma density in discharge column was measured by well known resonant method with using one resonator. Plasma introducing into cavity resonator leads to shift of resonant frequency and change resonant quality.

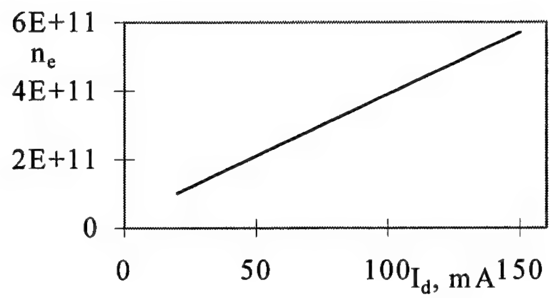



Fig.5.2. Dependence of plasma density $n_e$ on discharge current $I_d$

Fig.5.2 shows dependence of the plasma density averaged over tube diameter on discharge current. Linear in the discharge current dependence of plasma density corresponds usual glow discharge conditions. Gas-filled standard noise generator with thermoionic cathode and anode was used as a gas-discharge plasma source. For this tube at discharge current $I_d$ = 150 mA and discharge voltage $V_d$ = 195 V spectral power densities $P_1 = 63\ kT_0$ ($T_0$ = 293 K) for wave length $\lambda_1$ = 6 cm and $P_2 = 61\ kT_0$ for wave length $\lambda_2$ = 9 cm were measured. According to Rayleigh law for black-body radiation one can estimate plasma temperature $T_e \cong 1{,}8\times10^4$ K. For case of electron impact radiation and for frequencies lower than electron plasma frequency estimation of plasma density n $T_0 \cong 6\times10^{11}$cm$^{-3}$ correlated to experimental data was received.

**5.2. Experimental studies of CCC structures.**

Let's now pass to the results of experience with model CC SWS. Fig.5.3 shows effect of plasma on eigenfrequencies of axial modes in the coupled-cavity four-period-long SWS. Curve 1 corresponds to "empty" system ($I_d = 0$), curve 2 – discharge current $I_d = 20$ mA and consequently, plasma density $n_e \approx 1\times10^{11}$ cm$^{-3}$. As expected [5.1], the mode frequencies are upshifted by the plasma. Fig. 5.4 shows the same effect for higher plasma density ($I_d = 80$ mA, $n_e \approx 4\times10^{11}$ cm$^{-3}$).

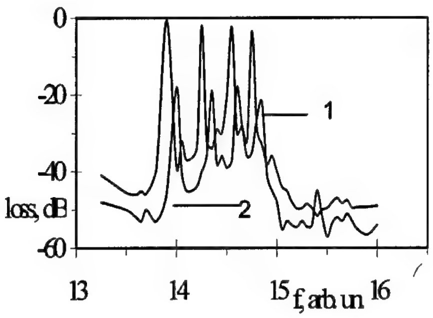



Fig.5.3. Effect on plasma resonant frequencies of CC SWS

Curve 1 - $I_d$ =0, curve 2- $I_d$=20 mA.

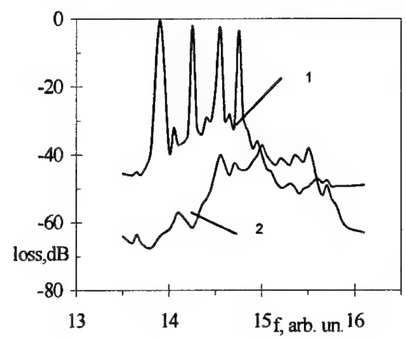



Fig.5.4. Effect on plasma resonant frequencies of CC SWS

Curve 1 - $I_d$ =0, curve 2- $I_d$=80 mA.

Assigning resonant axial number $k_{zn}$ to corresponding index one can reconstruct the dispersion diagram of the system. In Fig.5.5 the numerical results of the dependence of relative resonant frequency upshifts (R, %) on plasma density, based on NEVA program modification, are presented (solid curve). The experimental results for low band frequency and high band frequency are plotted by circles and crosses, respectively.

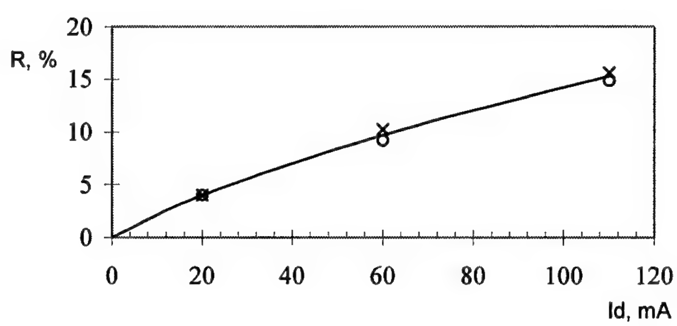



Fig.5.5. Dependence of relative resonant frequency upshifts on discharge current.

Solid curve – numerical result; points – experimental results

So, we present a new method for an experimental study of plasma loaded CC SWS, based on the use of autonomic gas-discharge plasma source with stationary mode of operation and regulable plasma parameters.

**Reference:**

5.1. G. Nusinovich, Yu. Carmel et al. IEEE Transactions on Plasma Science, Vol. 26, № 3, pp. 628 – 645, 1998.

# VI. Experimental investigations of the plasma TWT prototype model characteristics

## 6.1. The experimental equipment

Experimental investigation were carried out on models of plasma TWT for industrial application with main frequency 2,45 GHz.

The equipment for experimental researches of characteristics of the electromagnetic oscillations created by a plasma traveling wave tube (TWT), consists of three basic parts:

- Source of electromagnetic oscillations;
- The set of wave guide devices, units for distribution and absorbing energy of oscillations;
- The complete set of measuring devices.

The block-diagram of measurements of characteristics of the beam-plasma device is given in Fig. 6.1.

The source of electromagnetic oscillations consists of the master generator (driving oscillator) and the preliminary amplifier. As the master generator the serial measuring frequency generator of signals having output power on a calibrated output up to 1 mW, and on not calibrated output - up to 10 mW is used. The preliminary amplifier is made on the base of serial TWT and has output power up to 250 W.

The set of wave guide devices, units for distribution and absorbing energy of oscillations consists of a set of standard wave guide elements, consisting of three directed couplers, absorbing load and connecting wave guides. One of the directed couplers at the output of preliminary amplifier serves for measurement microwave oscillation power at the input of the plasma TWT. An isolator between the directed coupler and the input of the device serves to prevent penetration of the back wave in the preliminary amplifier and in the measurement circuit of input power. The first directed coupler at the output of plasma TWT serves for measurement of microwave oscillation power, and the second one – for observation of modulation envelope and signal spectrum. Absorbing load serves for utilization of electromagnetic oscillation energy.

The complete set of measuring devices consists of two low power calorimetric wattmeters (limits of measurements 0.01-20 W) and one high-power wattmeter (up to 6 kW), the spectrum analyzer , the detector, the oscillographs, the ammeter, the voltmeter and an instrument for measurement of hydrogen pressure (Fig. 6.1). Low power wattmeters are used for measurement of oscillation power at an input and at output of the device. The microwave oscillations are supplied at their inputs through directed couplers, having attenuation 30 and 40 dB.

The high-power wattmeter is intended for calibration directed couplers by a method of comparison of indications. The ammeter and the voltmeter serve for measurement of a current of a collector and a voltage on cathode of plasma TWT. The detector, oscillograph and spectrum analyzer serve for supervision modulation envelope and an oscillation spectrum. The measuring instrument of pressure serves for definition of pressure in the device at work in a plasma mode.

Key parameters describing work of plasma TWT breadboard models are dependence of an output microwave power on hydrogen pressure, on input signal power (the amplitude characteristic) and on frequency of amplified signal (amplitude-frequency characteristic), and also an amplification coefficient. The special equipment was used for research of noise characteristics and out-of-band oscillations.

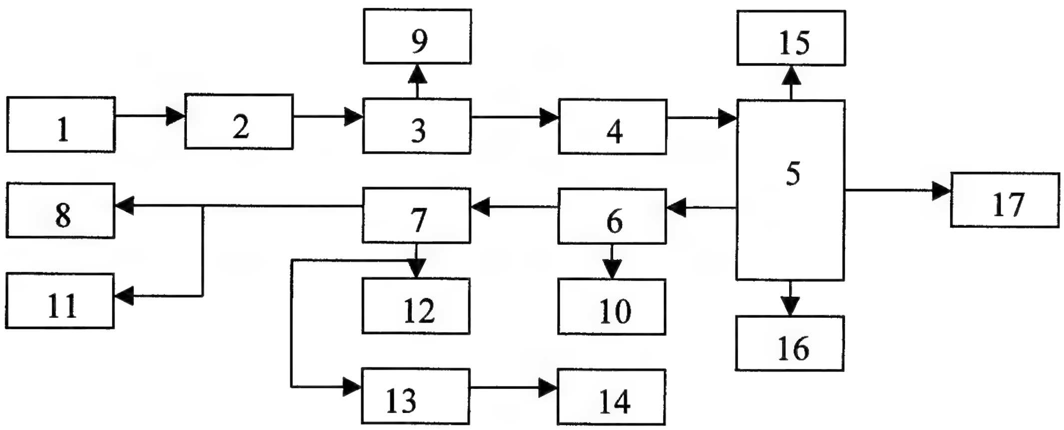



Fig. 6.1. The block-diagram of measurements of characteristics of the beam-plasma device
1 – master generator; 2 – preliminary amplifier;

3 – directed coupler; 4 – isolator; 5 – beam-plasma device;

6, 7 – directed couplers; 8 – absorbing load; 9, 10 – low power wattmeters; 11 – high power wattmeter; 12 – spectrum analyzer;

13 – detector; 14 – oscillograph; 15 – voltmeter; 16 – ammeter;

17 – hydrogen pressure measurement device

### 6.2. Results of experimental researches

At increase of hydrogen pressure from $10^{-5}$ up to 0,8-1,0x$10^{-3}$ mm Hg smooth increase of output power of the amplifier at constant power of an input signal occurs (Fig. 6.2) that is caused by increase of efficiency of interaction of an electron beam with plasma-wave guide system and the appropriate growth of resistance of communication(connection) of slowing down structure (3C). At pressure about 1,0x$10^{-3}$ mm Hg maximum of output microwave power is obtained (value of ~ 20

kW is obtained in tests, with electron efficiency ~ 30 %) , which 2-3 times increase of electronic efficiency corresponds.

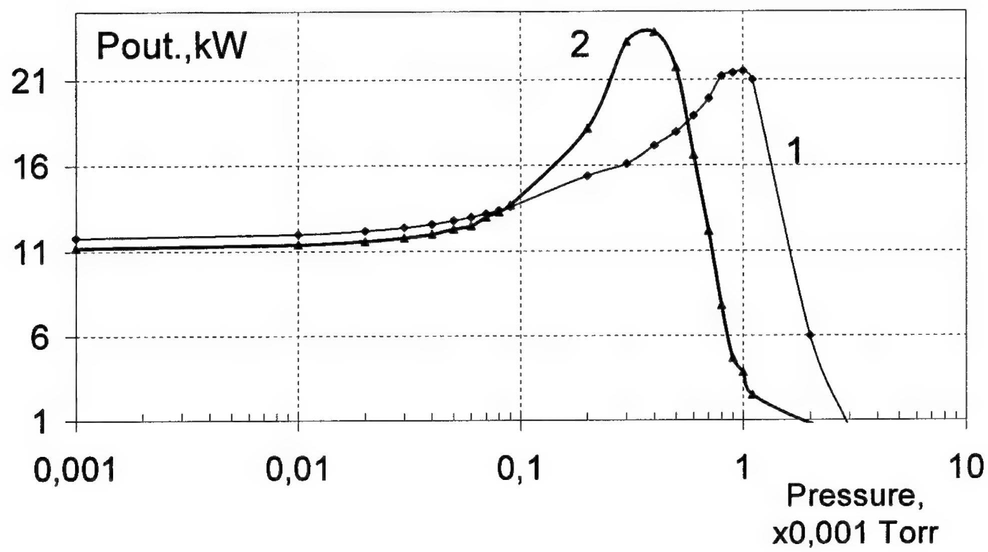
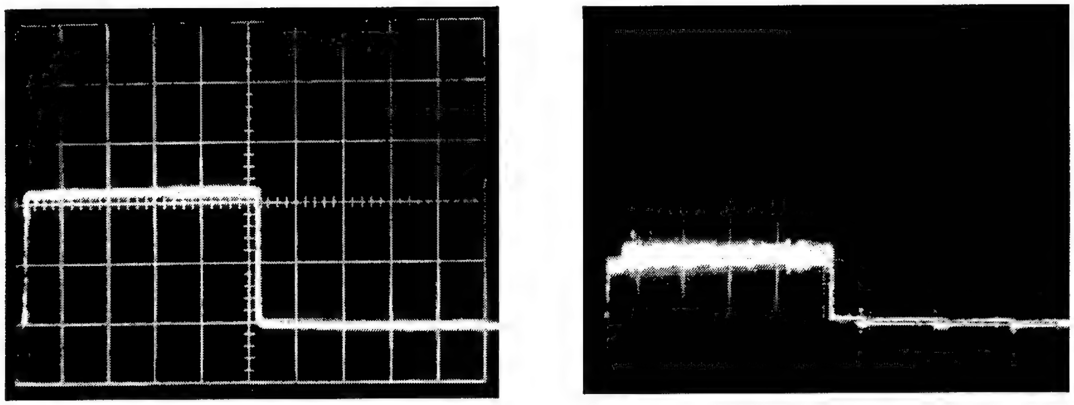


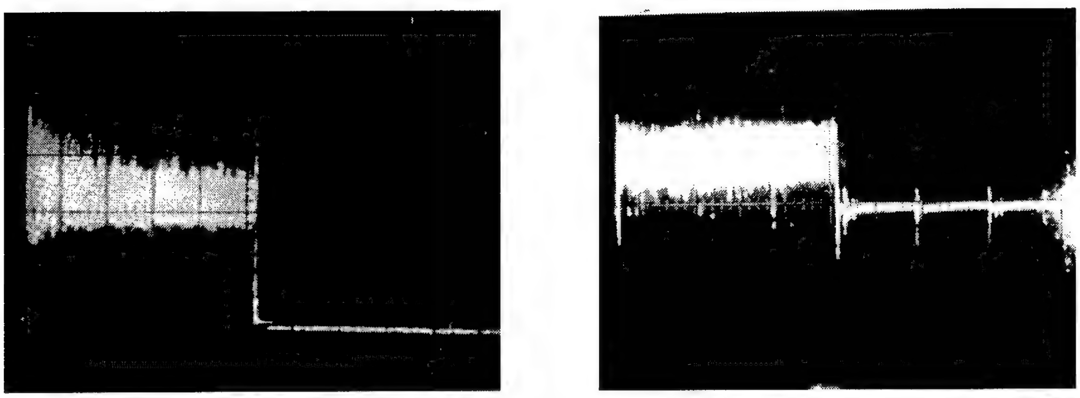

Fig.6.2. Dependence of output power on hydrogen pressure
Curve 1- Ucoll.=0; Curve 2-Ucoll.= -60 V.

The further pressure increase is accompanied by sharp drop of power and transition of a system in a mode of developed beam-plasma discharge. It is defined by dynamics microwave energy flows in plasma-resonators system and corresponds to the calculation data, when at the ratio of plasma frequency to the working frequency greater than 2, the general longitudinal energy flow is almost completely (on eighty percents) passes in the transit channel of the structure and radiation is absent. The appropriate oscillograms of a collector current and a current of losses (on SWS and the anode) are shown in Fig. 6.3.

At evolution of the intensive beam-plasma discharge a relaxation of an electron beam and 100% modulation of collector current occur, and the hybrid plasma-wave guide system breaks up. With it amplification of microwave oscillations stops and a level of output microwave oscillation power falls up to zero.



1)



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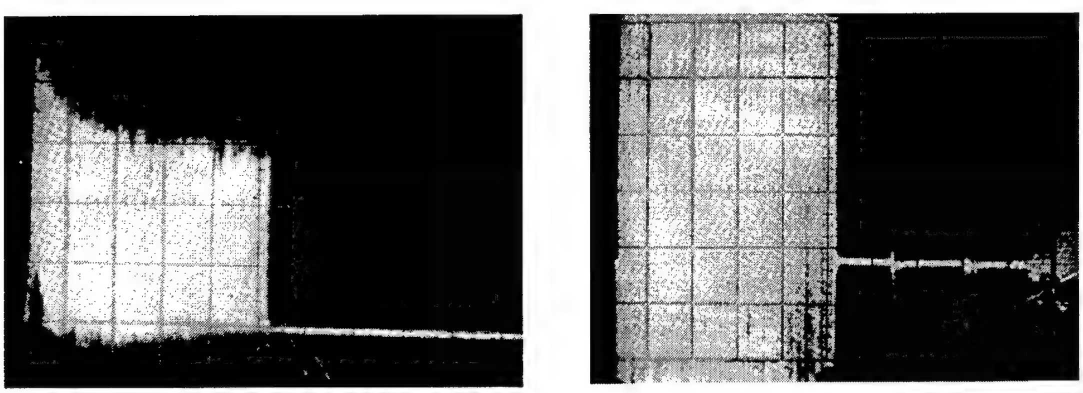


3)

**A** **B**

Fig. 6.3. Oscillograms of plasma TWT currents at the pulse accelerated voltage:

A – collector current; B – losses current (slow wave structure and anode)

1) $P=8*10^{-4}$ Torr; 2) $P=1.5*10^{-3}$ Torr; 3) $P=2.5*10^{-3}$ Torr;

Abscises scale : 2 ms/div
Ordinate scale: A – 1A/div; B – 0.1 A/div

The possible mechanism of restriction of maximum microwave oscillation power and occurrence of instability in plasma-wave guide systems is offered in [6.1].

For steady work of plasma-wave guide structure the following condition should be satisfied:

$$S_w < n_p k T_e \tag{6.1.}$$

Where $T_e$- electron temperature of plasma;

$S_w$ – density of microwave power oscillation;

$k$- Boltzmann constant;

$n_p$- plasma concentration.

Let's try to estimate a level of the greatest possible output microwave power. It is possible to proceed from the following ratios for concentration and temperature of plasma:

$$2\pi f_p = \omega_p = \sqrt{\frac{4\pi n_p e^2}{m_e}}\,; \tag{6.2.}$$

$$S_w = \frac{W_{1СВЧ}}{\Delta V} = \frac{P_{1макс}}{10^9 f_0 \Delta V} = \frac{P_{1макс}}{10^9 \pi a^2 d f_0} \tag{6.3.}$$

where:- $f_0$ – working frequency ( GHz);

-$P_{1макс}$ - maximum microwave power flow in the transit channel of SWS;

-$a$ – radius of the transit channel of SWS;

-$d$ – gap of CCC resonators between drift tubes.

Substituting 6.3. and 6.2. in an inequality 6.1., after some transformations we get the following for rough estimates:

$$P_{1\max} \leq 0{,}8 f_p^2 f_0 T_e \quad \text{(W)} \tag{6.4.}$$

where:- $f_0$ и $f_p$ – working and plasma frequencies, GHz;

- $T_e$- plasma electrons temperature, eV.

The level of the maximum output microwave power is determined under the ratio of power

flows in SWS – relation of $P_2$ to $P_{1\,max}$ in the transit channel:

$$P_{out} = \zeta \cdot P_{1\max}\ ,\ \text{where}\ \ \zeta = \frac{P_2}{P_1},$$

for CCC system we get value $\zeta$=30÷40. For the studied samples, at $T_e$=10 eV and $\zeta$=40, calculation gives value of maximum output power *Pout* =32 kW, which is close to the maximum values of output microwave power obtained in tests.

On the basis of the analysis of numerical modeling of the hybrid SWS such as CCC the conclusion about necessity of system engineering of rigid stabilization of plasma concentration in the transit channel of plasma TWT was made.

The structure with use of an additional source of collector potential and a feedback from output microwave power is offered. Except for the decision of a problem of keeping the optimum plasma concentration in the transit channel of CCC, the negative potential on a collector (in a range 50-100 V) provides the required value of output microwave oscillation power at smaller (by one and a half - two times) values of working gas pressure in the device (Fig. 6.2, a curve 2), reducing consuming of gas from the hydrogen generator, facilitating work of system differential pumping and increasing a service life of the device.

During researches of amplitude-frequency and amplitude characteristics (AFC and AC) the basic attention was given to the two effects, characteristic for plasma TWT:

- Increase of output oscillation power at plasma formation in the transit channel;
- Displacement of the top border of amplitude-frequency characteristics in area of higher frequencies and, as consequence the expansion of a working frequency band of the device.

All researches were executed on two plasma TWT experimental model samples with accelerating voltage of 15-16 kV. The first model had a beam current 3 A and equal number of resonators in the parts of slow wave structure providing formation of electron clusters and amplification of a signal. The second model was designed for a current 2 A.

The number of the resonators forming electron clusters, was reduced by 30 % and the number of resonators in the amplifying part is so increased.

In Fig. 6.4 the amplitude-frequency characteristics of the first device are submitted for vacuum and plasma modes of operation at constant power of an input signal.

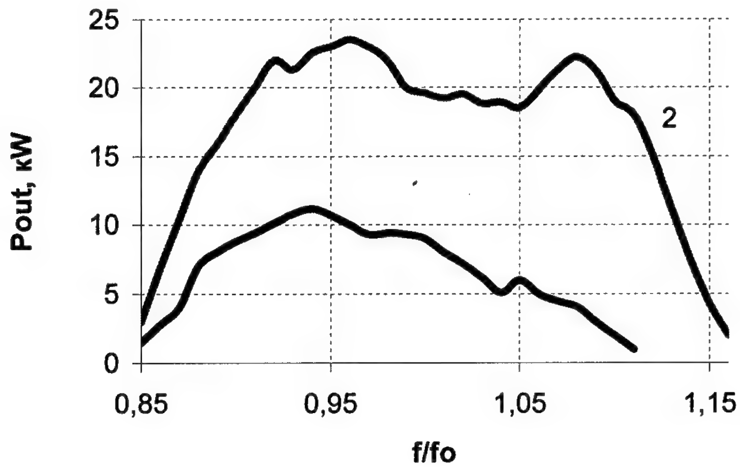



Fig. 6.4. Amplitude-frequency characteristics of the first model of plasma TWT.
1-vacum mode; 2-plasma mode. $f_0$ – mean frequency of the working frequency band.

Alongside with absolute increase of output power, a high-frequency part of the frequency characteristic and expansion of amplification band in the high frequency band in a plasma operation mode take place. It confirms results of theoretical researches. Similar character of amplitude-frequency characteristics corresponds to a mode of interaction of an electron beam with the space (volumetric) waves in the plasma-wave guide system. In Fig. 6.5 the amplitude characteristics of the first device in a plasma operation mode are given. Characteristics are obtained for three frequency values of the microwave laying within the working frequency band.

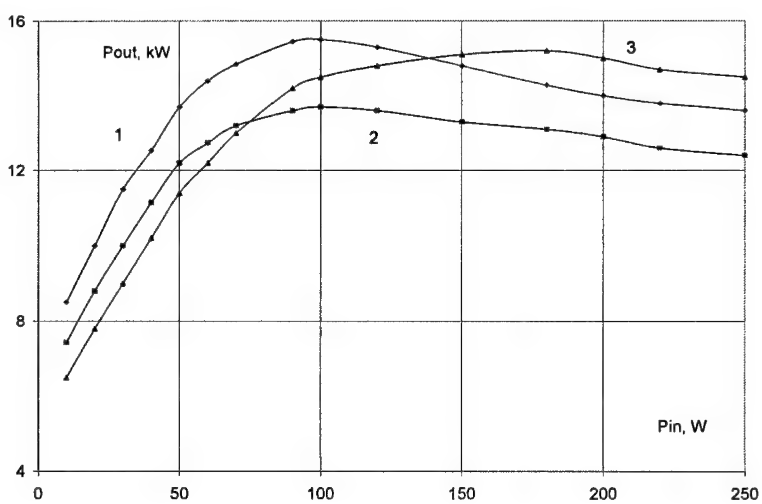



Fig. 6.5. Amplitude characteristics of the first model of plasma TWT at different working frequencies (plasma operation mode).

In Fig. 6.6 dependences of amplification coefficient on frequency in vacuum and plasma operation modes are submitted at the output power close to maximum value. It is visible, that transition in a plasma operation mode increases amplification coefficient approximately by 4 dB and expands a working frequency band. On the basis of this characteristic the maximum non-uniformity of amplification coefficient was calculated. At edges of a working frequency band (about 10 % from all the band) it does not exceed 0.03 dB/MHz, in other range of frequencies - no more than 0.01 dB/MHz. In a vacuum operation mode the maximum non-uniformity is much higher - 0.08 dB/MHz.

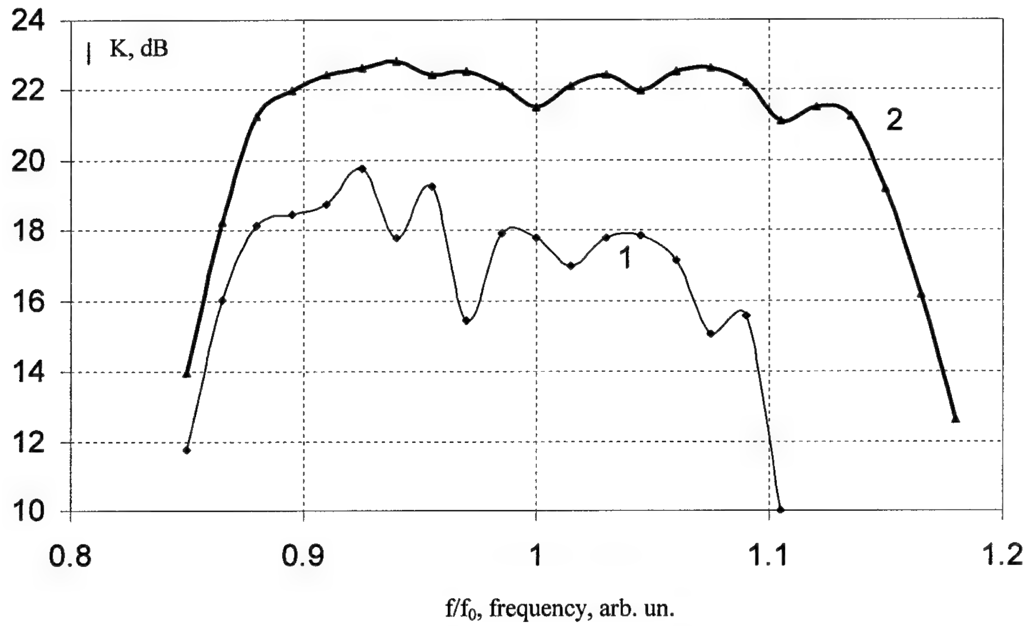



Fig. 6.6. Dependence of amplification coefficient on frequency for the first model of plasma TWT

1 – vacuum mode; 2 – plasma mode $f_0$ – mean frequency of the working frequency band.

The amplitude-frequency characteristic, amplitude characteristic and frequency dependence of amplification coefficient of the second device are submitted in Fig.6.7, Fig.6.8 and Fig.6.9.

In this device "the plasma effect" also is to the full shown: output microwave power is increased and the strip of working frequencies extends. However in comparison with the first device, this one has a half of maximum output power and less difference between powers in plasma and vacuum modes, especial in the low frequencies range. Both these phenomena are explained with reduction of an electron beam current.

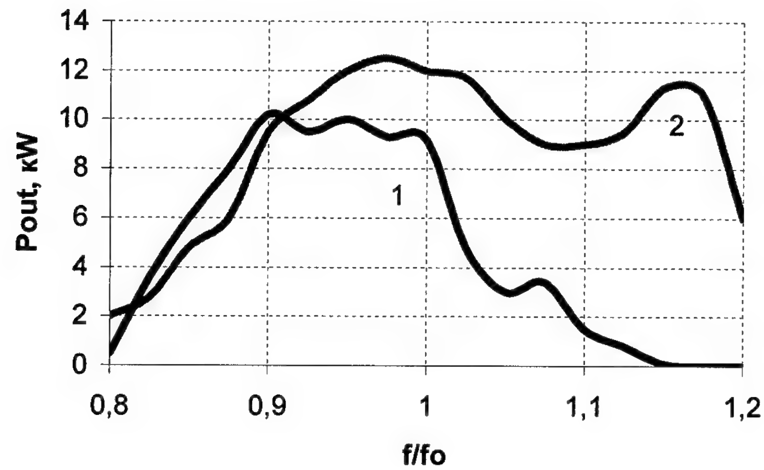
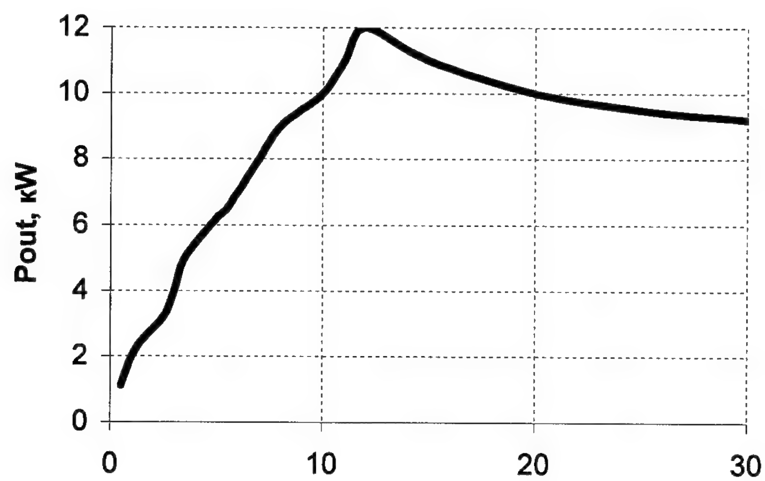



Fig. 6.7. Amplitude-frequency characteristics of the second model of plasma TWT

1-vacum mode; 2-plasma mode. $f_0$ – mean frequency of the working frequency band.




Pin, W

Fig. 6.8. Amplitude-frequency characteristics of the second model of plasma TWT at mean frequency of the working frequency band (plasma mode)

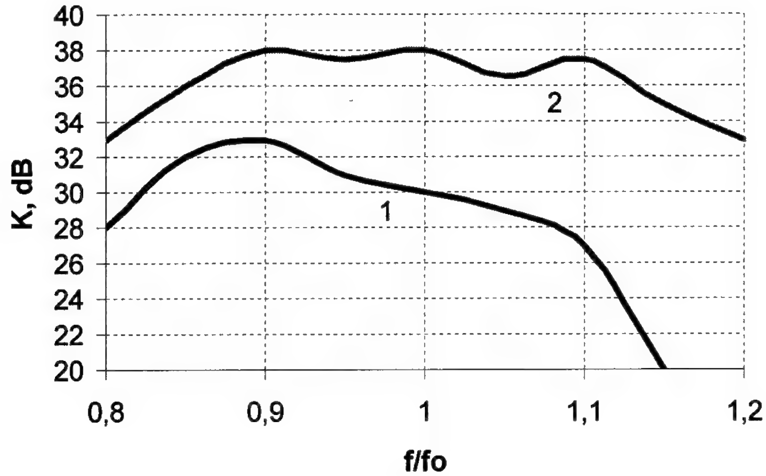



Fig. 6.9. Dependence of amplification coefficient on frequency for the second model of plasma TWT

1 – vacuum mode; 2 – plasma mode. $f_0$ – mean frequency of the working frequency band.

It should be noted, that the given amplitude-frequency characteristics showing essential increase of the frequency band in the plasma operation mode require additional analysis. With taking into consideration the wide frequency band the required range of accelerating voltages in the electron gun becomes less, and non-stability operation modes can arise on the borders of frequency band. Thus the obtained frequency band can be considered to be equal to 20%. It will be the following investigation program to research an opportunity of increase frequency band of the system.

**Reference:**

6.1 Ya.B. Fainberg. Yu. P. Bliokh, M.G. Lyubarsky et. Al. Electro dynamics of hybrid plasma-wave guide slow wave structures. Proceedings of Ukraina Academy of Science. No.11, p.77, 1990.

# VII. Research of multi-frequency amplification mode of plasma TWT

## 7.1. The analysis of amplification of signals with close frequencies.

Radio technical systems have to amplify not one separate signal, but the whole system of signals, which amplitudes in common case are different. With it the input signal spectrum represent a sum of different in amplitude and frequency signals, standing close each from other and coincided with the TWT amplification frequency band.

Passage through the amplifier of a complex input signal is accompanied by mutual amplitude and amplitude-phase modulation of each of harmonic components that results in nonlinear distortions of an output signal. As a result the ratio between amplitudes of separate components of an output spectrum will differ considerably from similar ratio at the input. Change of output signals in the total frequency band with change of an input signal level of one of frequencies represents cross-modulation and enrichment of a frequency spectrum of an output signal by combinational components represents inter-modulation.

These distortions are caused by complex nonlinear effects: change of amplitude modulation depth of each input signals at the TWT output which is caused by non-linearity of its amplitude characteristic, transformation of amplitude modulation of each signal to phase modulation at the output of the amplifier, caused by dependence of output signal phase shift on a level of input powers, at last, the cross amplitude and phase modulations causing occurrence of combinational components in an output signal spectrum. The specified effects result in distortion of useful signals and, hence, such distortions are undesirable with TWT work in amplifying mode.

The given section of the Report is devoted to theoretical and research of amplification mode of several harmonious signals by plasma TWT. In the first part the theoretical analysis of two-frequency amplification mode of plasma TWT, based on the approximated representation of a complex signal as quasi harmonic fluctuations with slowly varying amplitude and a phase is carried out.

The offered numerical calculation method can be used for calculation and analysis of an output signal spectrum of plasma TWT at multi-frequency influence, for studying inter-modulation and cross-modulation characteristics of hybrid devices. Then results of experimental researches of plasma TWT are presented in operation mode of amplification of several signals. Experimental installations and techniques for research of amplification mode of two harmonious signals are described and the developed techniques for realization of measurements are given.

The comparative analysis of vacuum and plasma operation amplification modes is carried out, the working parameters of plasma TWT providing a minimum level of nonlinear distortions at multi-frequency amplification mode are determined.

### 7.2. Theoretical analysis of multi-frequency operation

Necessity of the theoretical analysis of multi-frequency operation mode of plasma TWT is caused by the fact there is not enough experimental data on this subject, and the measurement technique is complex and requires a lot of man-hours..

At rather close frequencies of input signals the technique based on approximate representation of a complex signal as quasi harmonic one with slowly varying amplitude and a phase is applied. In this case it is enough to know the amplitude-phase characteristic of plasma TWT at working frequency. It can be received approximately by analytical way, or it is can be taken from experiment.

The input signal consisting of several harmonious oscillations can be presented as:

$$u_{in} = \sum_{k=1}^{i} u_k \sin(\omega_k t + \varphi_k) \qquad (7.1.)$$

where $i$— number of signals;

$\omega_k=\omega+\Omega_k$ - frequency of $k$-th signal;

$\varphi_k = \varphi + \Phi_k$ - phase of $k$-th signal;

$\omega$ and $\varphi$ - frequency and phase of the 1-st signal;

$\Omega_k$ , $\Phi_k$ - phase shift (difference) of frequencies and phases of the 1-st and $k$-th signal;

take input $\rho_k = {\Omega_k}/{\Omega}$, $\chi_k = {\Phi_k}/{\Phi}$, we receive:

$$u_{in} = \sum_{k=1}^{i} u_k \sin((\omega + \rho_k \Omega)t + \varphi + \chi_k \Phi) \qquad (7.2.)$$

Expression (7.2.) can be rewritten in the form:

$$u_{in} = A(\tau)\sin(\omega t + \alpha(\tau)) \qquad (7.3.)$$

where $A(\tau) = u_1 R(\tau)$;

$$R(\tau)=\sqrt{\sum_{k=1}^{i}\bar{u}_k^2+2\sum_{m=1+k}^{i}\sum_{k=1}^{i}\bar{u}_k\bar{u}_m\cos((\rho_m-\rho_k)\Omega t+(\chi_m-\chi_k)\Phi)}$$

$\bar{u}_k = {}^{u_k}\!/_{u_1}$ - amplitude of k-th signal, normalized to amplitude of the 1-st signal;

$$\alpha(\tau)=\varphi+arctg\frac{B_s(\tau)}{1+B_c(\tau)}$$ , where:

$$B_s(\tau)=\sum_{k=1}^{i}\bar{u}_k\sin(\rho_k\Omega t+\chi_k\Phi);$$

$$B_c(\tau)=\sum_{k=1}^{i}\bar{u}_k\cos(\rho_k\Omega t+\chi_k\Phi);$$

Here and below all the dependences from $\tau$ — slowly varying functions: $\tau=\Omega t$.

As far as $\Omega \ll \omega$ , $\Omega \ll 2\pi/T_0$, where $T_0$ — transit time of electrons through the slow wave system, that for the analysis of multi-frequency operation mode of plasma TWT it is necessary to know the amplitude and the phase-amplitude characteristics of the amplifier on frequency ω.

The output signal, as well as an input signal, will be modulated on amplitude and a phase:

$$u_{out}=C(\tau)\sin(\omega t+\beta(\tau)) \tag{7.4.}$$

where $C(\tau)=F[A(\tau)]$;

$\rho(\tau)=\alpha(\tau)+\psi(\tau)$;

$\psi(\tau)=F[A(\tau)]$.

$\psi(\tau)$ takes into account transformation of amplitude modulation in phase modulation.

By decomposition of expression (7.4.) in Fourier series on low frequency content (with a cycle $2\pi/\Omega$), it is possible to estimate the spectrum of output signal of plasma TWT at multi-frequency amplification.

Let's consider a special case when two-frequency signal is applied at the input of plasma TWT. Thus:

$$R(\tau)=\sqrt{1+\bar{u}^2+2\bar{u}\cos\Omega t}$$ ,

$$\alpha(\tau) = arctg\frac{\overline{u}\sin\Omega t}{1+\overline{u}\cos\Omega t} \quad \text{where:} \qquad (7.5.)$$

$$\Omega = \omega_2 - \omega_1 \quad , \quad \overline{u} = {}^{u_2}\!\big/_{u_1}.$$

Output signal, without consideration of additional phase shift as result of transformation of amplitude modulation in phase modulation, can be presented:

$$u_{out} = a_0 \sin\omega t + \sum_{\substack{k=-\infty \\ k\neq 0}}^{k=+\infty} u_k \sin(\omega + k\Omega)t \qquad (7.6.)$$

where: $a_0 = \dfrac{1}{2\pi}\int\limits_0^{2\pi} C(\tau)\cos\beta(\tau)d\tau$;

$$a_k = \frac{1}{2\pi}\int\limits_0^{2\pi} C(\tau)\cos\beta(\tau)\cos k\tau\, d\tau;$$

$$b_k = \frac{1}{2\pi}\int\limits_0^{2\pi} C(\tau)\sin\beta(\tau)\sin k\tau\, d\tau;$$

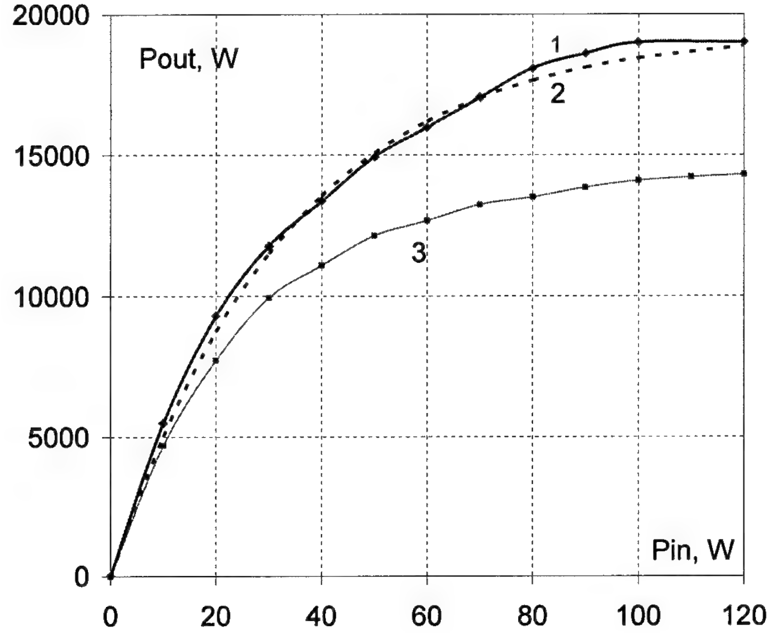
for $k>0$ $\quad u_k = \dfrac{a_k + b_k}{2}$; at $k<0$ $\quad u_k = \dfrac{a_k - b_k}{2}$.

For calculation under formulas 7.4 - 7.6 in the software package "Mathcad" the special program was developed. At calculation of the amplitude characteristic (ACH) of a sample plasma TWT $F\ (A_{input})$, (see Fig..7.1, here a curve 1- is an experimental ACH-dependence of an output microwave power on a level of input power at one-frequency amplification, curve 2- is an approximated dependence received on the basis of a sedate polynomial). The program allows to calculate (for the given input powers $P_{1\ input}$ and $P_{2\ input}$ ) (powers of input signals $f_1$ and $f_2$) values of the following components:

$P_{1output}$ и $P_{2output}$ – powers of main combinational components of the first order (output signals frequencies $f_1$ *and* $f_2$);

$P_{12output}$ and $P_{21output}$ – powers of main combinational components of the third order ( output signals frequencies $2f_1 - f_2$ and $2f_2 - f_1$);

$P_{13output}$ and $P_{31output}$ – powers of combinational components of the fifth order (output signals frequencies $3f_1 - 2f_2$ and $3f_2 - 2f_1$);




1 – experimental curve, 2 – approximated characteristic, 3 – amplitude characteristics (dependence of output microwave power $P_{out}$ on the total input power $P_{inp}$ at two-frequency amplification)

Fig.7.1. Amplitude characteristics of plasma TWT prototype

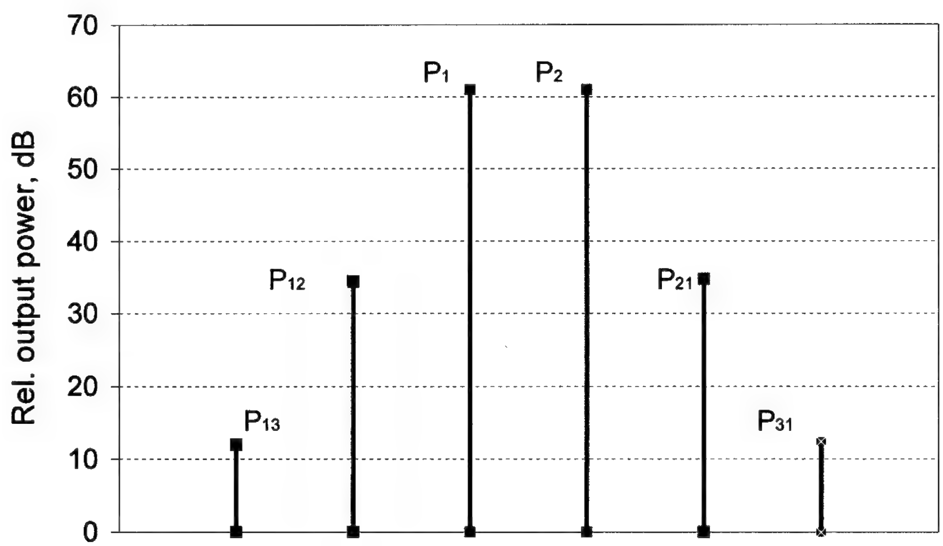



Fig.7.2. Calculated spectrum diagram of output signal of plasma TWT at amplification of two input signals with $P_{1int}$=$P_{2int}$=20 W

Simultaneously relative power levels of combinational components are calculated.

The calculated spectral diagrams of output signal of plasma TWT are given in Fig. 7.2 and 7.3 for various ratios of input signals level. According to diagrams, at applying two signals with close frequencies on plasma TWT input the combinational components arise in a spectrum of an output signal which frequencies are determined by ratios $2f_1$-$f_2$ и $2f_2$-$f_1$, $3f_1$-$2f_2$ and $3f_2$-$2f_1$ etc.

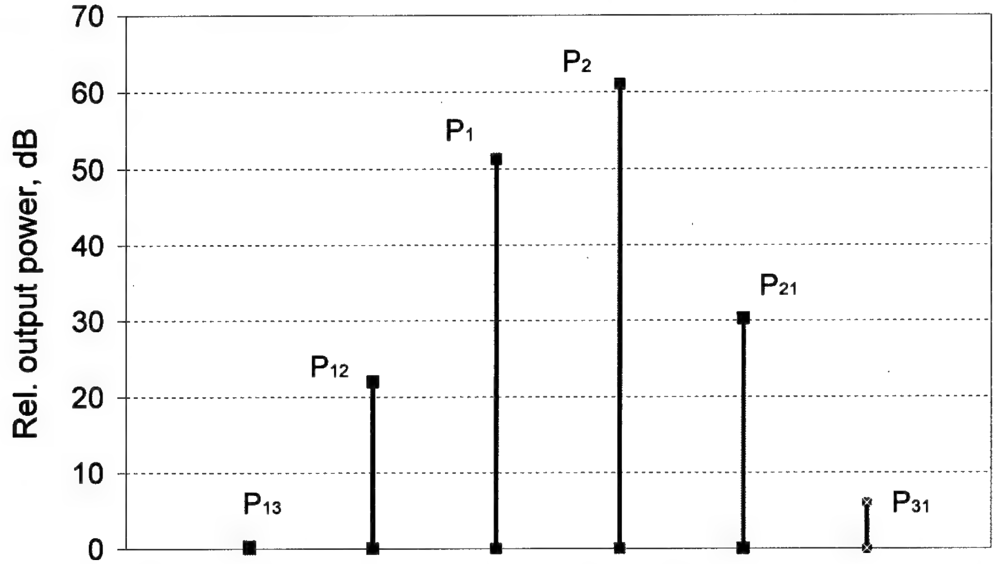



Fig.7.3. Calculated spectrum diagram of output signal of plasma TWT at amplification of two input signals with $P_{1input}$ = 5 W, $P_{2input}$ = 40 W

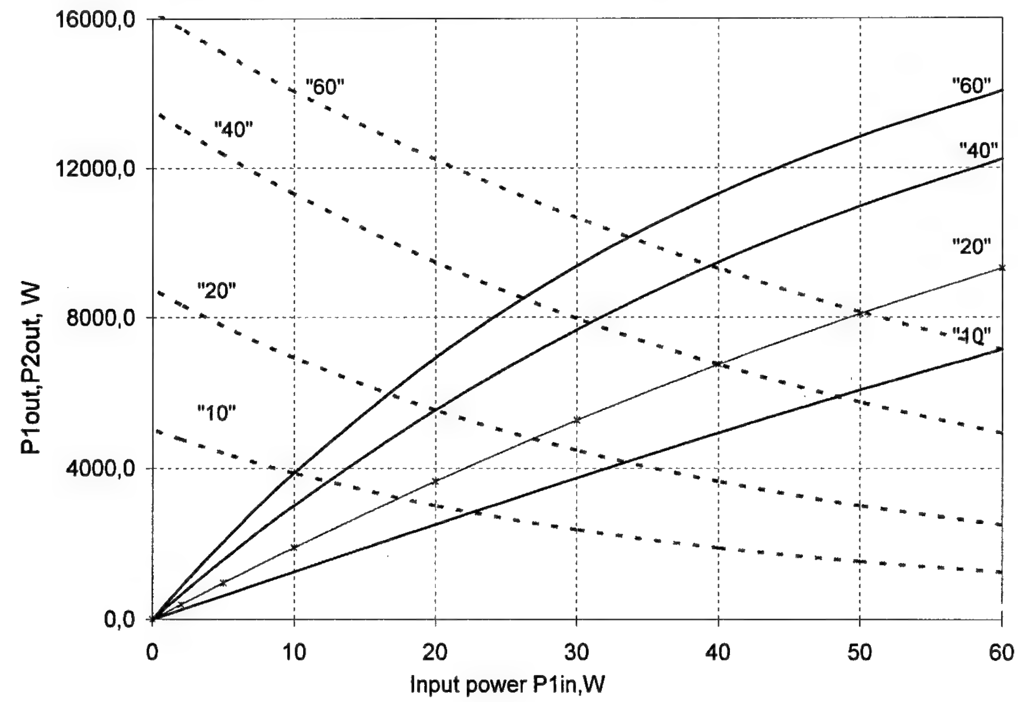



Fig.7.4. The graph of dependences of basic signals output power $P_{1out}$ (solid curves) and $P_{2out}$ (dotted lines) on the first signal input power level $P_{1in}$ at different fixed levels $P_{2int}$ (values $P_{2int}$ are designated in watts near the corresponding curves)

We should note, if combinational components of the second order with frequencies $f_1 \pm f_2$ are far away on their frequencies from applied signals and do not coincide with amplification band,

the combinational components of the third order with frequencies $2f_1 - f_2$ $2f_2 - f_1$, are close by frequencies to applied signals and can amplified intensive in the Slow Wave System (SWS). The second current harmonic excites high enough field of twice frequency, so it should be expected intensive signal amplification on the combinational frequencies.

Various dependences of combinational components level for a spectrum of output signal from input signals ratio (calculated cross-modulated characteristics) are shown in Fig. 7.4 (for the basic output signals), and in Fig. 7.5 (for a level of the combinational components of the third order) and in Fig. 7.6 (for a level of the combinational components of the fifth order). The analysis of these dependences allows to make the following conclusions:

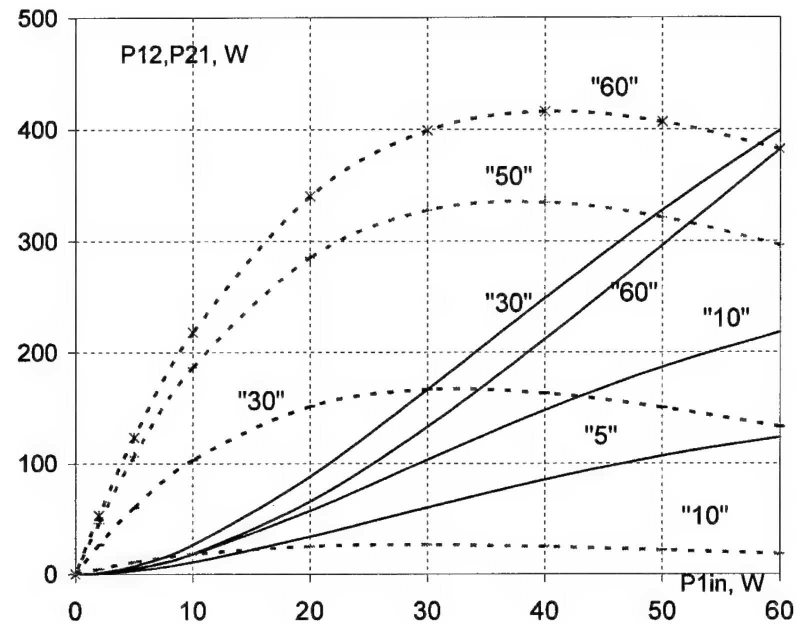



Fig.7.5. The graphs of dependences of output power of combinational components of the third order $P_{12out}$ (dotted lines) on input power level of the first signal $P_{1in}$ at different fixed levels of $P_{2in}$

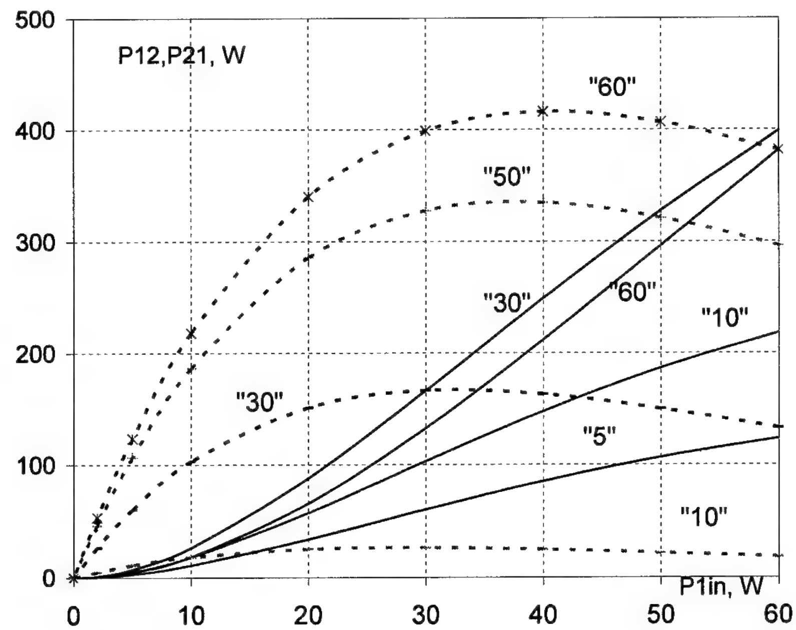



Fig.7.6. The graphs of dependences of output power levels of combinational components of the forth order $P_{13out}$ (solid curves) and $P_{31\ out}$ (dotted lines) on level of input power of the first signal $P_{1in}$ at different fixed levels of $P_{2in}$

From the curves in Fig. 7.4 – 7.6 it is seen, if output power of one of signals prevail essentially over the other one, the level of main signals on the output and a level of their combinational components depend weekly on input powers ratio. When one of signals prevail over another one, its amplification efficiency is close to plasma TWT amplification efficiency.

Mutual influence is shown only in the values area ($P_{1in}/P_{2out}$ from —10 dB to +10 dB. Anyone can see, that at equal input powers levels of output power of the appropriate components also are equal.

At increase of difference in initial amplitudes the compactness of bunches of a smaller signal decreases first of all. Because of it at initial space interaction areas the signal having the big input amplitude prevails. In the field of saturation of a prevailing signal decomposition of its bunches can result as to "crispate" the bunches of the second signal not grouped completely, and in growth of their compactness and relative increase of a level of the second signal.

Total output power of the basic components at simultaneous amplification of two signals is less than the output power received at amplification of a single-frequency signal with power equal to total power of input signals at multi-frequency amplification mode (look at curve 3 in Fig. 7.1 amplitude characteristic of a plasma TWT – the dependence of output microwave power from the total input power at amplification of two signals of equal power with close frequencies).

Above mentioned results of calculations are coordinated with the experimental results received on a sealed-off breadboard model of plasma TWT. Dependence of a relative level of combinational components of the third and fifth orders at amplification of two frequencies of equal input power is shown in Fig.7.7. the calculated and experimental spectral diagrams of an output signal of plasma TWT are given in Fig. 7.8.

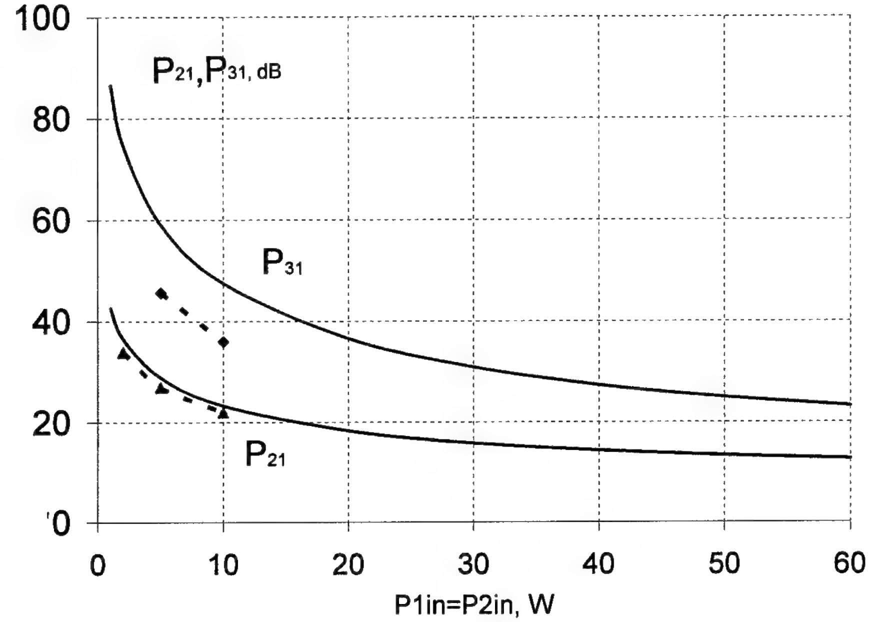



Fig.7.7. The graphs of dependences of calculated (solid curves) and experimental (dotted lines) relatively the level of combinational components of the third and the fifth order $P_{21out}$ and $P_{31out}$ on input power level ($P_{1in} = P_{2in}$)

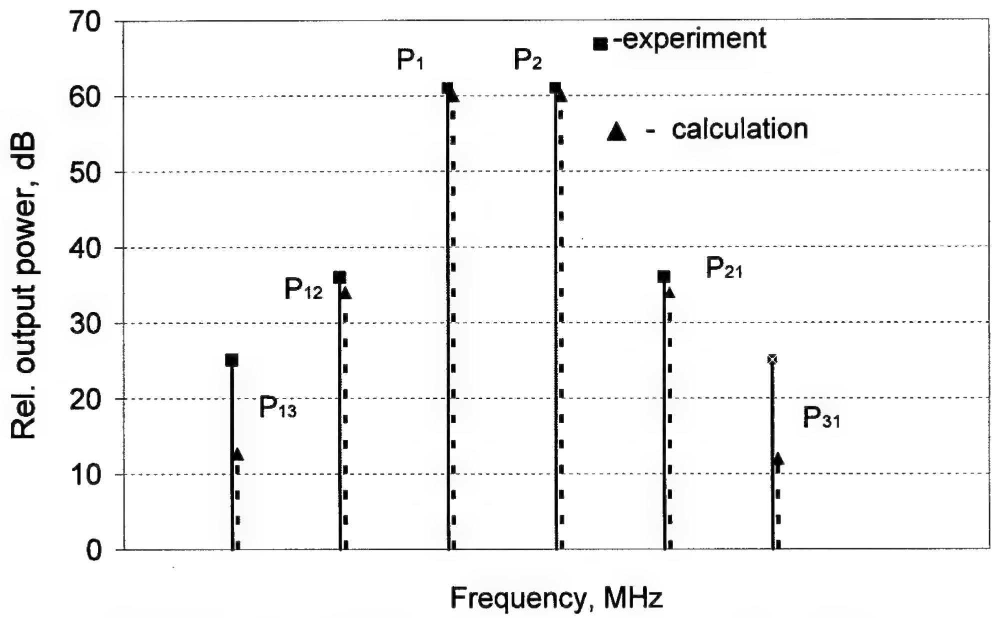



Fig.7.8. Experimental and calculated spectrum diagrams of output plasma TWT signal at amplification of two input signals, at $P_{1in}$=$P_{2in}$=20 W

Thus, the used numerical calculation method can be used for the analysis of an output signal spectrum of plasma TWT in researches of simultaneous amplification modes of several harmonious signals with close frequencies.

### 7.3. Experimental researches of two-frequency operation mode of plasma TWT.

At the first stage of researches inter-modulation characteristic of plasma TWT was investigated in the system with one preamplifier. The block-diagram of experimental measuring installation is submitted in Fig. 7.9. Here G1, G2 - driving generators, PA - the preamplifier; DC1, DC2 - directed wave-guide couplers, PM1, PM2 - calorimetric power measuring instruments; PC – wave-guide phase circulator; F - the filter; plasma TWT - the-plasma-beam amplifier; L - absorbing loading (matched); CA - the spectrum analyzer.

The standard microwave generators G4 were used as the driving generators. The bogey tube with a spiral TWT was used as a preamplifier. Calorimeter power meters PM1 and PM2 were watt-meters of type M3-54 and M3-56 correspondingly. The directed couplers, phase circulator and a matched absorbing loading were attested serial wave-guide devices with calibrated frequency characteristics.

For reduction of combinational components level a special microwave filter - the retuning volume resonator was used. The spectrum analyzer S4-60 was used for research of spectrum.

Researches were carried out by a technique of comparison of vacuum and plasma operation modes of plasma TWT. The beam-plasma amplifier worked in vacuum and plasma modes. Input power of the amplifier was put on equal 25-30 W. At such power level the plasma TWT works on a linear part of the amplitude characteristic both in vacuum and plasma operation modes. Cathode voltage of the beam-plasma amplifier was within the limits of 16,5-17 kV, the current of a collector was 1,8-2,1A. The amplifier worked in a pulse-frequency mode, i.e. the voltage on the cathode was applied with pulses of 4 ms duration and the pulse repetition period of 40 ms. Output signal pulse power of the beam-plasma amplifier in a vacuum mode was 2,5-2,8 kW in a plasma mode - 5,5-6,1 kW. Frequencies of driving generators were set equal to $f_1$ and $f_2$. At these frequencies the filter **F** has a minimum attenuation. The filter damps signals level on combinational frequencies at the output of preamplifier considerably (not less than by 10 dB).

For definition of absence or presence of signals on combinational frequencies and their level comparing with signals on main frequencies ($f_1$ и $f_2$) the spectrum analyzer S4-60 was used, which in turn was connected with the input of preamplifier PA (points G1 and G2 in Fig. 7.9.), to output of circulator PC (point 2), output of filter F (point 3) and to output of plasma TWT (point 4).

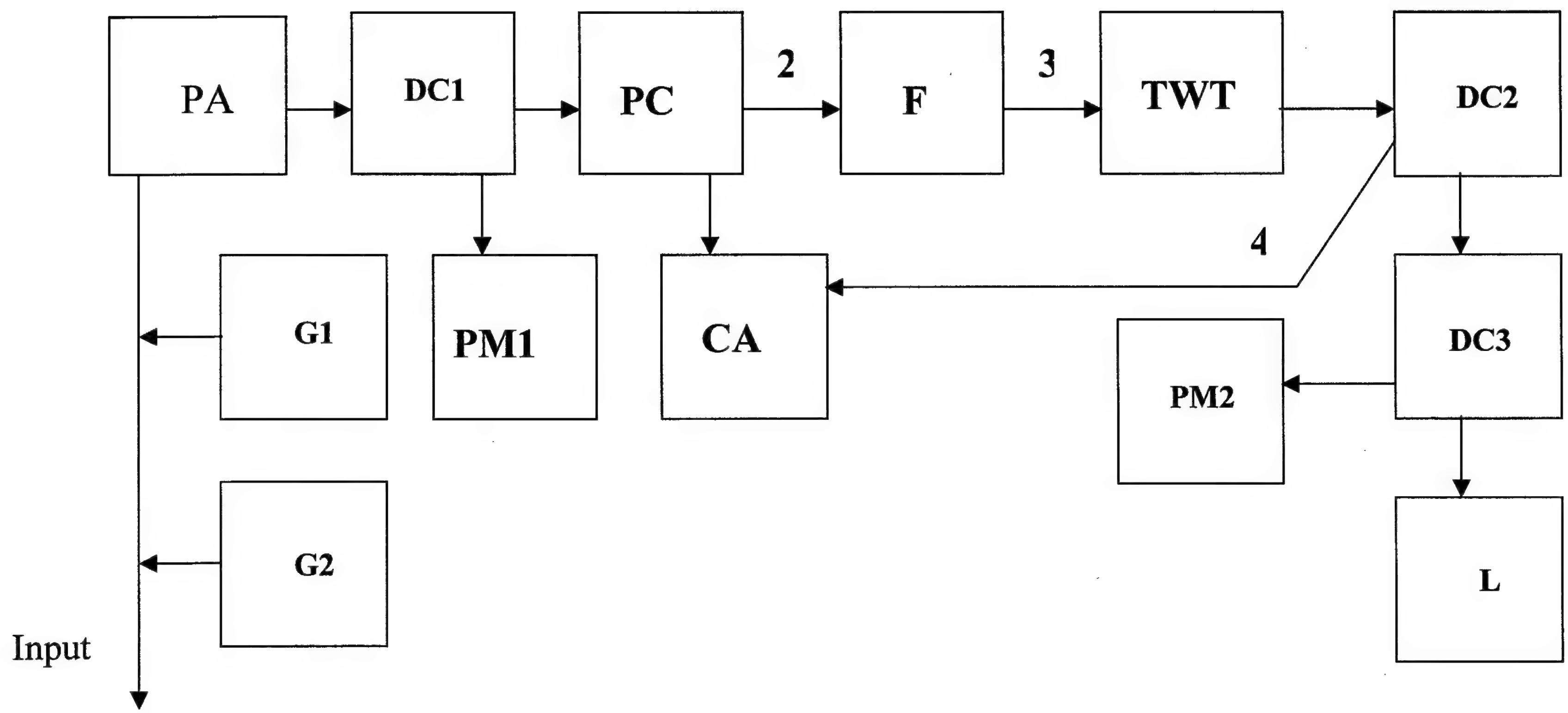



Fig.7.9. The diagram of measurements of combinational components I in the double-frequency operation mode

G1, G2 – the standard driving signal-generators, PA – preliminary amplifier, PC – phase circulator, F – frequency filter, DC1-3 – directed couplers, PM1, PM2 – calorimetric power meters, CA – panoramic spectrum analyzer , L – matched loading

Results of experiment are submitted in Table 7.1. Here are the measured levels of signals on the combinational frequencies in the vertical columns, normalized concerning levels of signals on the basic frequencies *f1* and *f2* measured in different points of the measuring installation.

Frequency separation in the experiment was $df = f_2 - f_1 = 70$ MHz. Hyphens in the columns mean that there is no signal indication on the given frequencies in the given points ( a level of the signal is lower than spectrum analyzer noise, that is less than –50dB).

Table 7.1 ( $df = f_2 - f_1 = 70$ MHz )

| Frequency, MHz | $f_1$-3df | $f_1$-2df | $f_1$-df | $f_1$ | $f_2$ | $f_2+df$ | $f_2$+2df | $f_2$+3df |
|---|---|---|---|---|---|---|---|---|
| Point of spectrum measurement | dB | dB | dB | dB | dB | dB | dB | dB |
| Output PA (point1) | - | - | - | 0 | 0 | - | - | - |
| Output PC (point 2) | -44 | -30 | -18 | 0 | 0 | -18 | -37 | -45 |
| Filter output F (point 3) | -45 | -46 | -35 | 0 | 0 | -29 | -38 | -45 |
| Output of plasma TWT (point 4), Vacuum mode | -46 | -35 | -25 | 0 | 0 | -24 | -33 | -46 |
| Output of plasma TWT (point 4), Plasma mode | -44 | -37 | -28 | 0 | 0 | -27 | -36 | -43 |

The carried out measurements allow to draw the following conclusions:

a) At applying on an input of the preamplifier of two signals with frequencies *f1* and *f2* there is a complex signal containing combinational frequencies *f1-k (df)* and *f2+k (df)*, where *k = 1, 2. n*, *df = f1-f2* – separation of frequencies of amplified signals. A maximum level of signals on combinational frequencies of the third order is lower by 23-25 dB in vacuum operation mode and by 27-28 dB in plasma operation mode.

b) the plasma TWT has a complex spectrum of output signal with combinational frequencies of different orders. Total power of output signals on combinational frequencies of the third orderis of 0,6-1,3 % from output signal power on the basic frequencies At the following stage of researches of the plasma TWT characteristics at simultaneous amplification of two harmonious signals with close frequencies investigations were carried out with the help of the circuit with two independent preamplifiers.

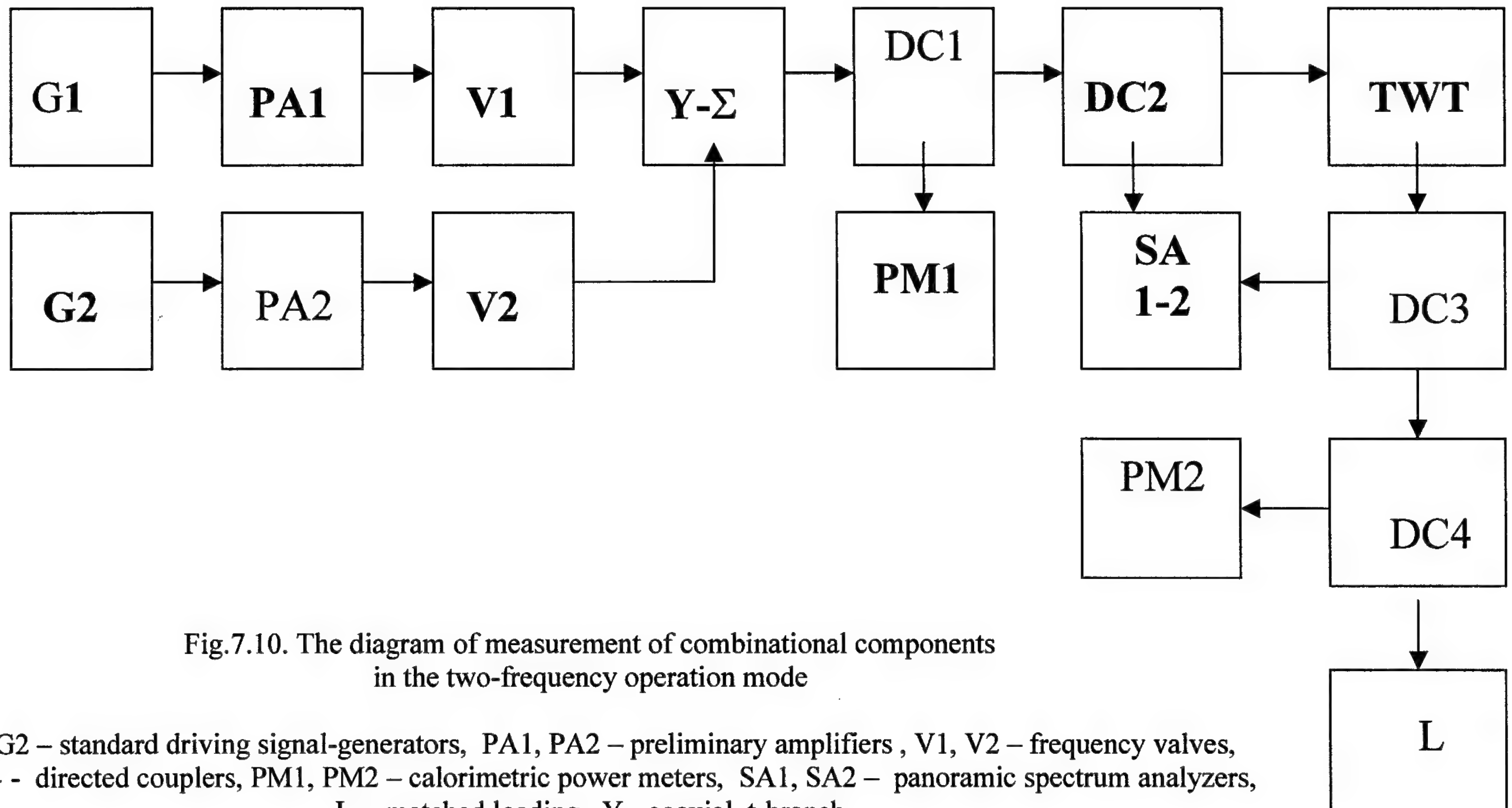



Fig.7.10. The diagram of measurement of combinational components in the two-frequency operation mode

G1, G2 – standard driving signal-generators, PA1, PA2 – preliminary amplifiers , V1, V2 – frequency valves, DC1-4 - directed couplers, PM1, PM2 – calorimetric power meters, SA1, SA2 – panoramic spectrum analyzers, L - matched loading, Y- coaxial t-branch

The block diagram of the experimental measuring installation is submitted in Fig. 7.10. The diagram in many respects is similar to the circuit of the previous measuring installation. Here PA1 and PA2 – are preamplifiers connected with the help unidirectional microwave valves V1 and V2, and a signal from preamplifiers are summarized with the help of a Y-tee. Researches were carried out by a technique of comparison of vacuum and plasma operation modes of plasma TWT. The beam-plasma amplifier worked in vacuum and plasma modes. Total power on an input of the amplifier was put equal 25-30 W. At such input power plasma TWT both in vacuum and in plasma modes works on a linear part of the amplitude characteristic (approximately 10 dB below a saturation level). Measurements were carried out at frequencies separation of input signals equal 5 MHz, 10 MHz, 20 MHz. Essential distinction in a level of combinational components of an output target signal at different frequencies separation is not revealed.

There is an output spectral diagram of plasma TWT in Fig. 7.11 at microwave output power by 10 dB lower of saturation level. In a plasma operation mode a level of combinational components of the third order drops a little bit in comparison with a vacuum operation mode, from –25 dB in vacuum mode and from –29 dB in plasma mode. Apparently, it is connected with phenomena of increase of grouped electron bunches in the hybrid beam-plasma SWS. Inter-modulation characteristic of plasma TWT are given in Fig.7.7. Anyone can see satisfactory concurrence with the calculated curves.

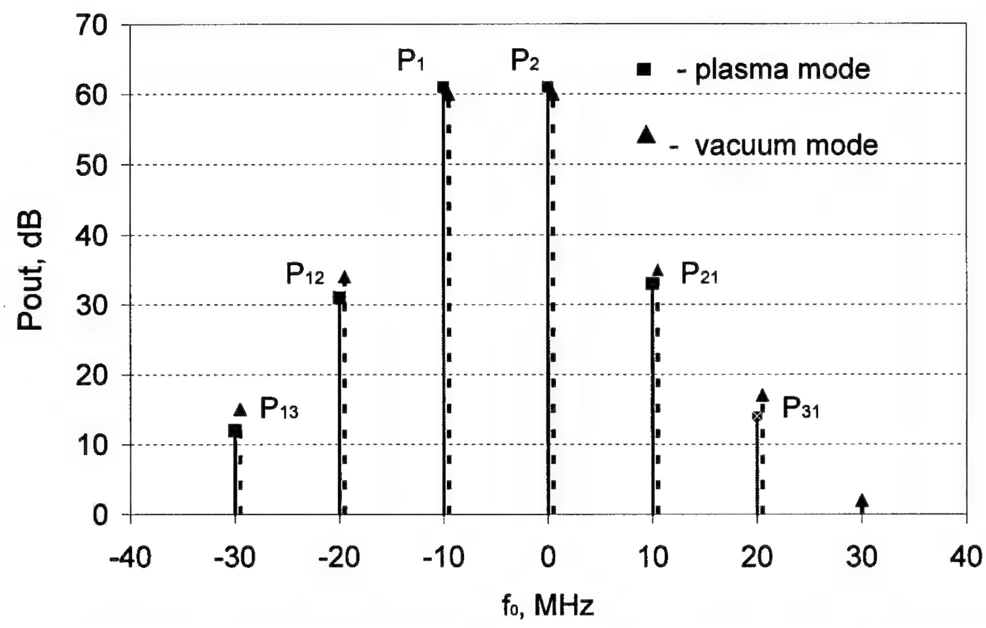



Fig.7.11. Experimental spectrum diagrams of output signal of plasma TWT at amplification of two input signals, $P_{1\,in}=P_{2\,in}=20$ W for vacuum (dotted curve) and plasma mode (solid curve)

## VIII. Research of self-noise of plasma TWT models

Experimental investigations of plasma TWT self-noise were carried out in two stages.

On the first stage the plasma TWT was investigated in plasma and in vacuum operation modes at output signal power of 10 kW. Power supply was provided in the pulse-frequency mode. Analysis of the frequency spectrum was made with the help of spectrum power density meter (SPD) ISPM-1 based on the gyromagnetic transducer, that was done by A.A. Kitaitsev et al. (Moscow Power Institute).

Sensibility of ISPM-1 meter in the working frequency band was better than 0.5 x $10^{-9}$ W/Hz. Results of measurements are submitted in Fig. 8.1. The TWT working frequency band takes up 8.6÷9.7 relative units interval (S). At power density of narrow-band noise oscillations on frequency 8.8 relative units of 0.4 mW/MHz in the vacuum operation mode (solid line) the relation of noise power level in a silence mode (input signal is absent) to output amplified signal power was not more than -53 dB.

In plasma TWT plasma operation mode (dotted lines) the narrow-band noise oscillations were displaced on frequency without change of amplitude. The frequency spectrum outside of the working frequency band was enriched with the occurrence of components with small amplitude and division of a spectrum in two parts in the area of higher frequencies.

The appropriate ratios of noise power levels to amplified microwave signal power have not been changed within the limits of measurement error.

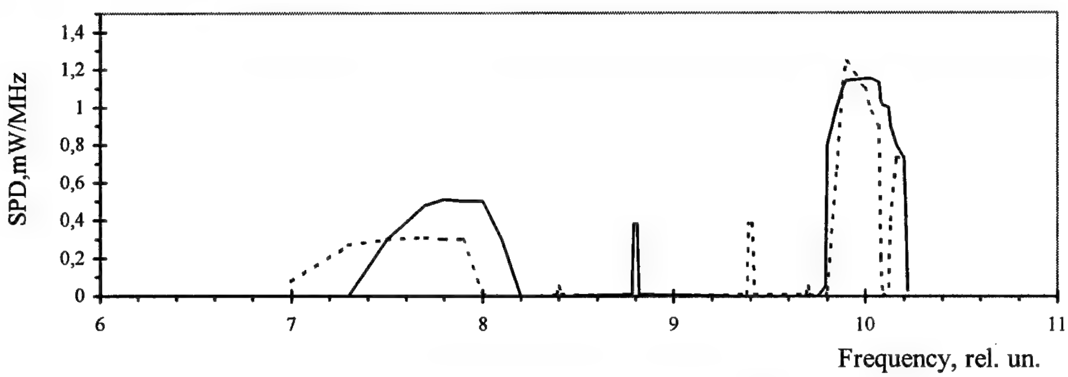
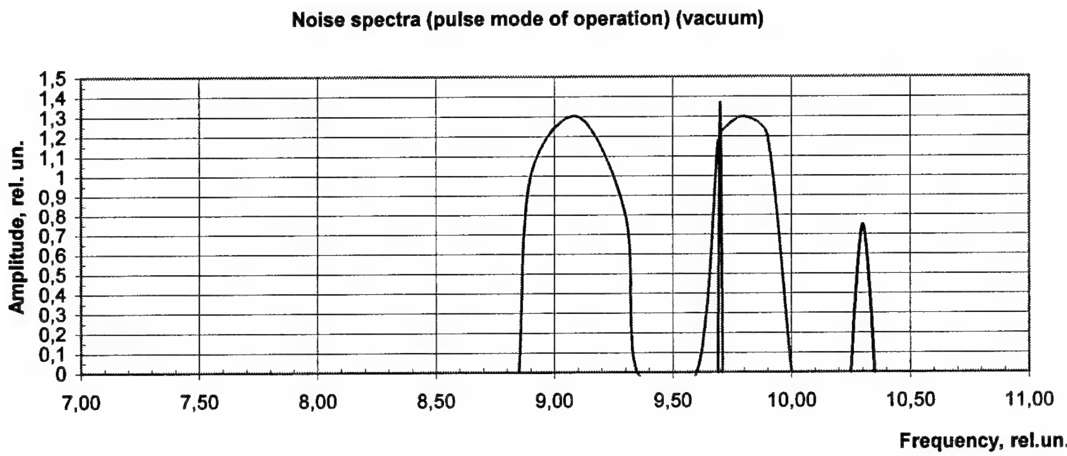



Fig. 8.1. Noise spectrum of plasma TWT

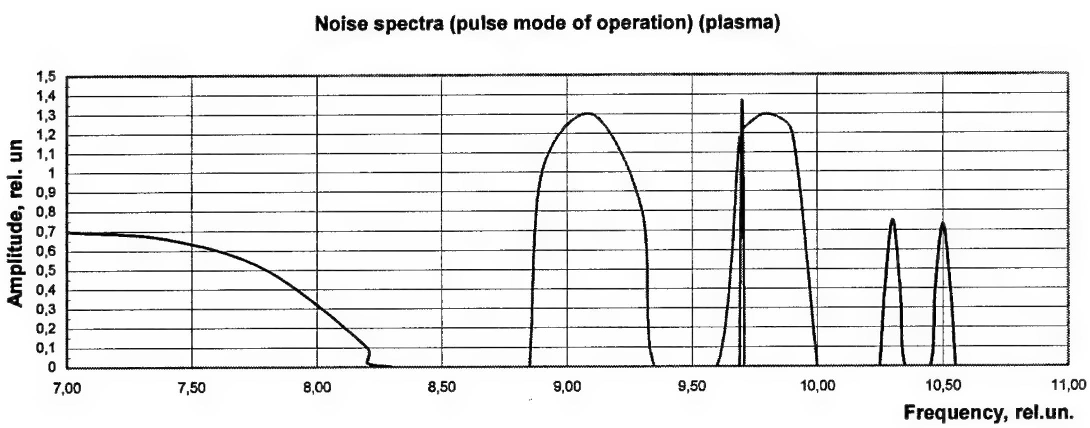
The second stage of investigation was carried out on plasma TWT at 2 kW output microwave signal power in both the pulse operation mode and operation mode with the pulse front clip-off. The last operation mode was necessary because the analysis has shown that the big contribution to the frequency spectrum is brought with the parasitic microwave oscillations arising in conditions of self-excitation of plasma TWT at the front and the decay of a power supply pulses.

Investigations were carried out with the help of the spectrum analyzer SK 4 with 10 MHz frequency bandwidth.

Noise spectrum at pulse power supply mode is shown in Fig. 8.2, a) - vacuum operation mode, b – plasma operation mode.




a)

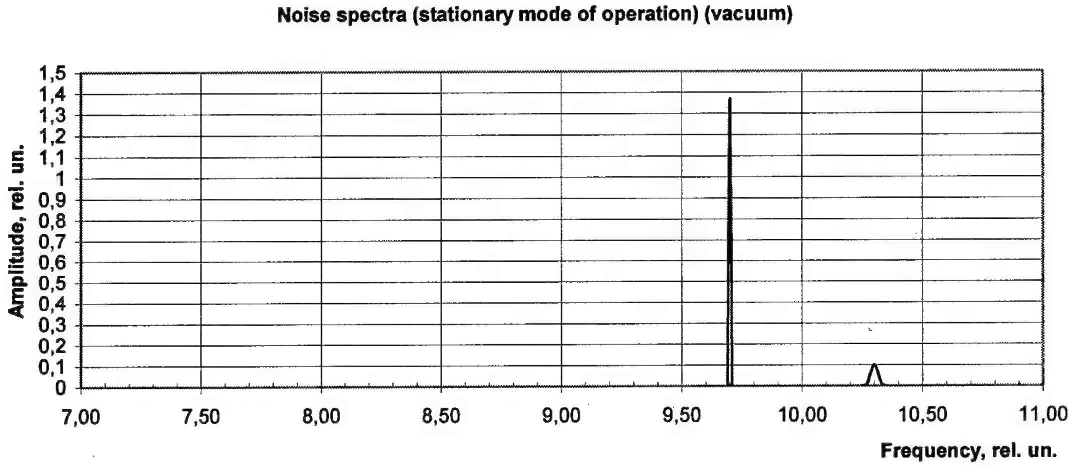



b)

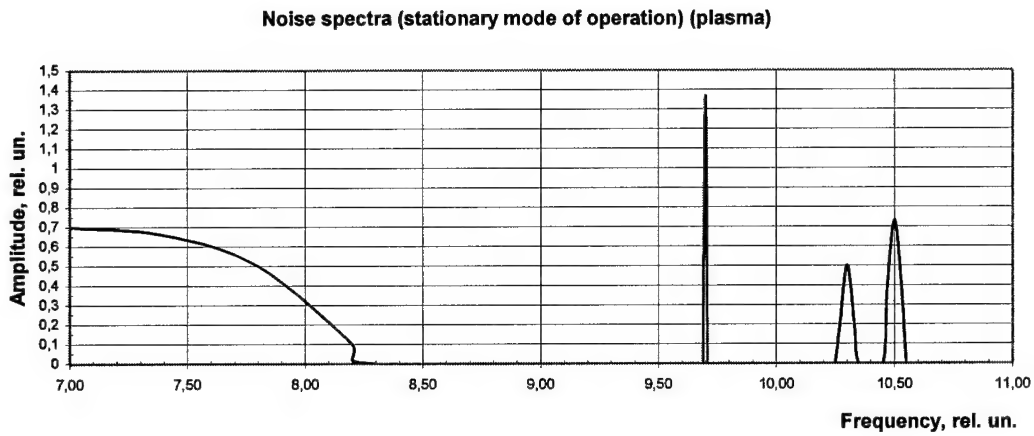
Fig. 8.2. Noise spectra (pulse mode of operation)
a) “vacuum” b) “plasma”

Noise spectrum in the operation mode with the front clip-off is presented in Fig.8.3 (23), a) – vacuum operation mode, b)- plasma operation mode.

The values of frequencies (relative units) in Fig. 8.1, 8.2, 8.3 are coincided. Amplitudes of spectrum power density in Fig.8.2. and 8.3 are approximately 10 dB less than amplitudes in Fig.8.1.




a)




b)

Fig. 8.3. (23) Noise spectra (stationary mode of operation)
a) "vacuum" b) "plasma"

Spectra corresponded with the power supply pulse operation mode contain slipping on frequency oscillations in the frequency area from 9 to 10 relative units, both in vacuum and plasma operation modes (red lines, Fig.8.2 a, b).

These oscillations disappear in the continuous operation mode (Fig. 8.3). Therefore we relate these oscillations with the parasitic microwave oscillations arising in conditions of self-excitation of TWT at the fronts of power supply pulses. The narrow-band noise oscillations (10.3 – 10.5 relative units), been out of high frequency of working bandwidth, was becoming double one in the plasma operation mode (Fig.8.2 and Fig.8.3).

Low frequency noise oscillations (7-8 relative units) were found in the plasma operation mode (Fig. 8.2b , Fig. 8.3b).

The obtained results allow us to establish the ratio of the noise power to the plasma TWT output power, which was equal to -60 dB in the working frequency operation band.
Previous experimental results show that the level of the inter-band noise in the plasma operation mode was nearly equal to noise power in the vacuum operation TWT mode.

Possible applications of plasma TWT's in communication systems will determine the course of further investigations of noise characteristics of these systems.

# IX. Research of out-of-band oscillations of beam-plasma amplifier

### 9.1. Installation for measurement of out-of-band oscillations.

In the given section the description of methods of measurement of the out-of-band oscillations, the diagram of the measuring installation and results of measurements of out-of-band oscillation levels of the beam-plasma amplifier on frequencies up to the third harmonic inclusive are submitted. It is shown, that on a relative level of out-of-band oscillations the beam-plasma amplifier is comparable with traditional high power amplifiers.

The installation for measurement levels of out-of-band oscillations (OBO) of power microwave devices consists of wave-guide oscillations separator (WOS) carrying out space separation of basic and out-of-band oscillations, converters of wave types (CWT) and selective pulse watt-meter (SPW) with a complete set of frequency-selective gyromagnetic converters, allowing to carry out amplitude analysis of selected out-of-band oscillations.

WOS consists of a separator of the basic and out-of-band oscillations and of the wave-guide switch. These unique devices have been developed by V.S. Buryak et al. (Moscow Power Institute). The separator of oscillations has, besides input and output channels of standard cross-sections inserted in the disconnection of the high-power channel, three measuring channels of square cross-section. The measuring channels of WOS are beyond cut-off for signals of basic oscillations. Signals on frequencies of out-of-band oscillations income into measuring channels as different types of waves $H_{mn}$ and $E_{mn}$ with a small known transient attenuation. Power of these types of waves is a subject of the further measurement. Power of the basic oscillation is allocated with the help of the probe located in one of the measuring wave guides, and this power also can be measured with help of selective pulse watt-meter (SPW). The diagram of the measuring installation is shown in Fig. 9.1.

The wave-guide switch is used for serial connection to each measuring channel of a frequency - selective pulse watt-meter or the matched load.

The complete set of measuring CWT serves for transformation waves of type $H_{mn}$ and $E_{mn}$ in the multi-wave measuring WOS output in a wave of type $H_{10}$ in the standard wave-guide of square cross-section.

Frequency-selective power meter for microwave oscillation power consists of a measuring attenuator and a selective pulse watt-meter (SPW). The primary gyromagnetic converter of SPW carries out frequency-selective conversion of microwave oscillation in a radio-signal with a carrier frequency 10 MHz and amplitude proportional to peak power and repeated the envelope of the microwave oscillations.

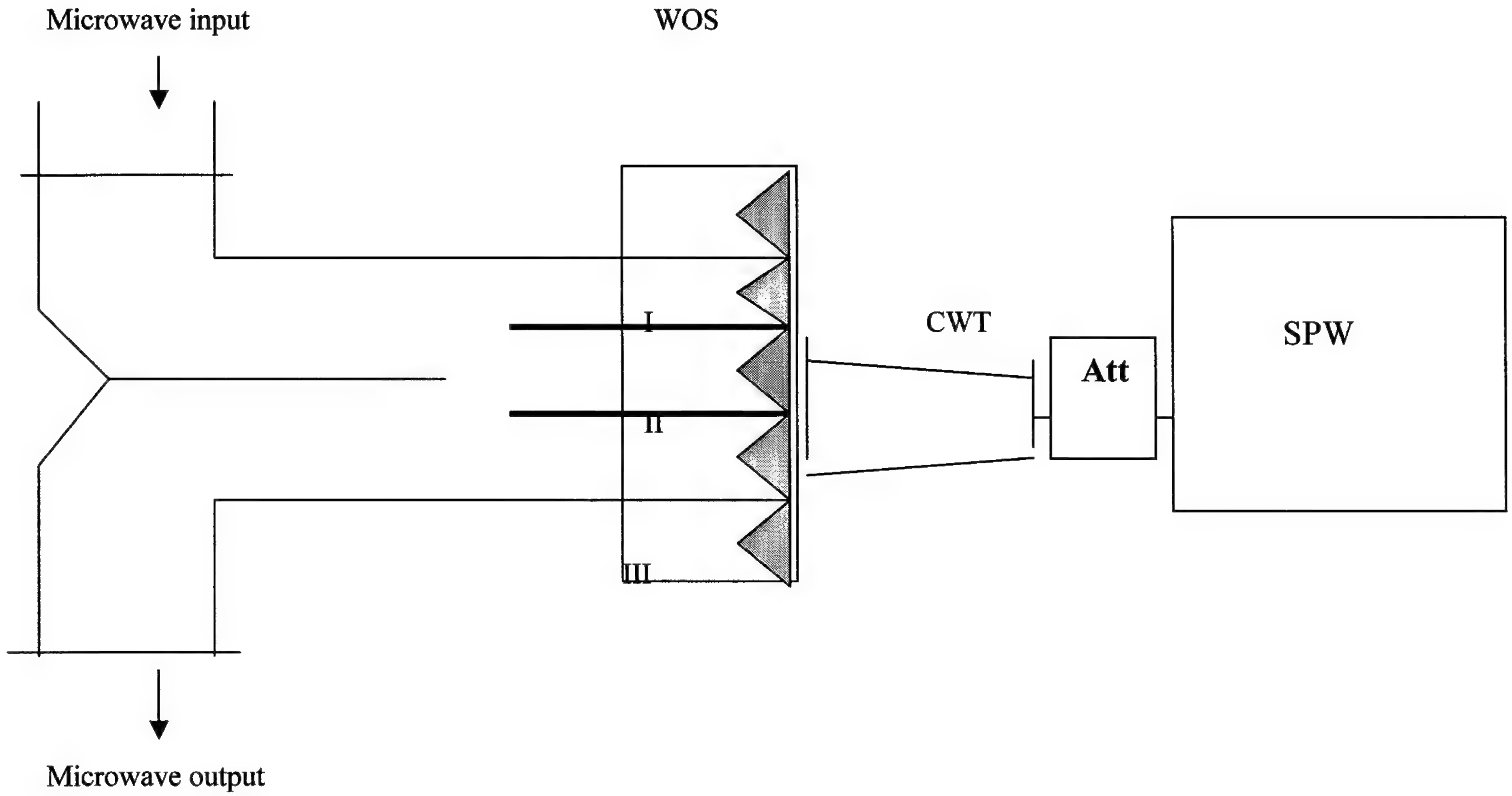



Fig.9.1. The diagram of measuring installation for research of OBO level
WOS – wave-guide oscillation separator, CWT – converter of wave types,
Att –microwave attenuator, SPW – selective pulse watt-meter

The frequency band of measuring microwave oscillations from 2 GHz up to 40 GHz is provided with several gyromagnetic converters. Minimum measuring power is of several milliwatt.

Measurement of OBO level was made on each of OBO frequencies by summation of results of measurements of power values, transferred by various types of waves in the measuring wave-guides of WOS. For this purpose to each measuring channel the measuring CWT are serially connected which quantity is determined by number of waves types in a measuring wave-guide.

OBO power on each frequency is defined as the sum of powers of each of spreading types of waves in each of three measuring wave guides. Thus, the total OBO power in a researched range is defined as following:

$$P = k \cdot \sum_{i=1}^{3} \sum_{j=1}^{n} 10^{0.1A_{ij}} \cdot P_{ij}$$

where k - calibration coefficient of WOS on OBO frequency, $P_{ij}$- OBO power in the $i$-th measuring WOS wave-guide on the $j$-th type of wave, measured by SPW, $A_{ij}$- attenuator damping in dB at measurement of $P_{ij}$.

The error of OBO measurement in the multi-wave operation mode of the basic WOS does not exceed $\pm 3$ dB.

**9.2. Results of measurements**

The block-diagram of the experimental installation is given in Fig. 9.2.

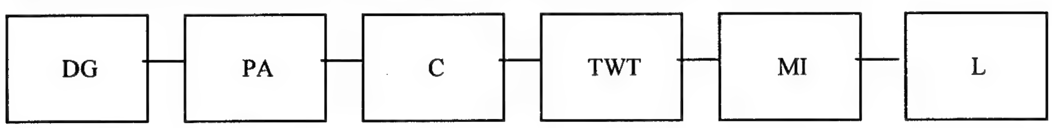



Fig.9.2. The diagram of measurement microwave OBO levels of beam-plasma amplifier. DG – microwave oscillations driving generator; PA – preamplifier of microwave oscillations; C – insulating circulator; TWT – beam-plasma amplifier; MI – measurement installation (Fig. 9.1); L – matched microwave loading

Measurements were carried out as follows. Powerful microwave radiation from output of the microwave preamplifier (PA) was applied at the input of the beam-plasma amplifier (TWT) working in the vacuum operation mode. The measured relative levels of the second and third harmonics from the preamplifier (PA) at exiting frequencies $f_0$ and $0{,}95f_0$ proved to be less than – 55 dB and did not introduce errors in OBO measurements. Frequency and power level of microwave oscillations were set up with the driving generator (DG). The accelerating voltage of an electron gun of the tube were modulated with periodical pulse sequence with pulse duration 5 ms and pulse period 50 ms. The only fluctuation on the second harmonic frequency was recorded at the output of

the tube working in the linear dynamic range on the basic frequency $f_0$ of the working frequency band with pulse power more than 2 kW in the frequency band $(1,3 - 2,9)f_0$ (microwave oscillations on other frequencies were not registered on other frequencies).

The sensitivity threshold of the measuring equipment on this frequency was of $-55 \div -58$dB . The microwave fluctuation represented a pulse with fluctuating envelope from a pulse to a pulse with an overshot at the front of duration about 0.5 ms.

Results of measurements of peak power on channels and types of waves on measuring WOS output on frequency of the second harmonic are given in Table 9.1.

**Table 9.1. Power level P on the second harmonic frequency, mW.**

| | WOS channel number | | |
|---|---|---|---|
| Wave type | I | II | III |
| $H_{10}$ | front – 34<br>top - 4,3 | "O" | "O" |
| $H_{01}$ | "O" | "O" | "O" |
| $H_{11}$ | front- 0,9<br>top - 0,9 | "O" | "O" |
| $E_{11}$ | "O" | "O" | "O" |

The oscillations having a level which is lower than a sensitivity threshold of the measurement equipment, are designated in table 9.1 as "O". The relative level of OBO at the output of the amplifier on the second harmonic frequency, in view of losses in a connecting cable (3dB) was of - 42 dB on an overshot at the front a pulse and - 50 dB on a flat top of a pulse. At frequency of excitation $f_0$ there was no microwave oscillations revealed in a frequencies band $(2,8 \div 4,2)$ $f_0$. OBO oscillation of the greatest intensity on the third harmonic frequency was revealed on the excitation frequency $0,95f_0$ at pulse power of the basic oscillations about 3 kW. Results of measurements are submitted in Table 9.2.

Thus, the relative level of OBO level on frequency of the third harmonic in view of losses in a cable (7 dB) at excitation frequency $0,95f_0$ was - 43 dB on overshot at fronts and - 45,5 dB on the flat top of a pulse.

Research of OBO at work TWT in a plasma mode has shown, that character and levels OBO on frequencies of harmonics have not changed.

**Table 9.2. Power level P on the third harmonic frequency, mW.**

| | WOS channel number | | |
|---|---|---|---|
| Wave type | I | II | III |
| $H_{10}$ | front– 8,0<br>top – 4,5 | front– 1,0<br>top – 0,4 | "O" |
| $H_{01}$ | "O" | "O" | "O" |
| $H_{11}$ | "O" | "O" | "O" |
| $E_{11}$ | "O" | "O" | "O" |
| $H_{20}$ | front– 0,5<br>top – 0,3 | "O" | front– 7,0<br>top – 4,5 |

In the conclusion we shall note, that the carried out measurements have confirmed high efficiency of use of the developed method of measurement and the control of OBO levels.

It is shown, that on OBO level the beam-plasma amplifiers are comparable with traditional amplifiers of a high power level. The OBO level on the second harmonic (on top of a pulse) meets the standard requirements on the out-of-band oscillations of radio transmitting devices (-50 dB, 100 mW). The OBO level on the third harmonic can be reduced by optimization of supply mode and plasma TWT operation mode control that demands additional researches.

Thus, under the basic characteristics the beam-plasma amplifier meets the requirements of the output powerful amplifiers of radio transmitting devices.

## X. The analysis of plasma TWT application in the radio communication systems

The radical way of information transfer speed increase and increase of jamproof – is application of broadband information systems. The broadband information system is the system, which transmitting signal occupies very wide frequency band considerably surpassing those minimum frequency band which is necessary for information transmitting. In modern broadband systems a signal can occupy a frequency band of some megahertz. It is necessary to provide double signal modulation on bearing frequency by a transmitted information signal and a broadband coding signal.

The transfer capacity of the channel is calculated with the equation:

$$C = W \cdot \log_2\left(1 + {}^{P_S}\!/_{P_d}\right), \tag{10.1}$$

where:

C – information efficiency (Shannon limit) (speed of transfer of the information), bit per second;
W – frequency band occupied with the channel, Hz ;
$P_S$ – signal power;
$P_d$ - masking disturbance power .

The equation (10.1) establishes connection between an opportunity of realization of correct transfer of the information on the channel with the given relation of powers – signal / disturbance and the frequency band allocated for transfer of the information. The equation shows, that for increase of information efficiency it is necessary to expand the frequency band and to increase signal power.

Changing in (10.1) basis of the logarithm, we receive $C = 1.44W \cdot \ln\left(1 + {}^{P_S}\!/_{P_d}\right)$.

At values $P_s/Pd \leq 0.1$ (which is quite typical for jamproof systems) $C \approx 1.44W \cdot {}^{P_S}\!/_{P_d}$ or $W \approx C \cdot P_d / (1.44 \cdot P_S)$.

Hence there is a direct dependence between the frequency band, information efficiency (Shennon limit) and relation of power disturbance / signal.

At the analysis of systems relation of powers signal / disturbance it is expedient to replace with the relation of signal energy $E_s$ to energy of disturbance Ed. We shall designate this relation with a symbol q.

If in a signal frequency band W the disturbance has uniform spectral power density $\nu_d$, than $E_d = \nu$ . Therefore at signal duration T it can be written down (10.2):

$$q = \frac{E_S}{\nu_d} = \frac{P_S \cdot T}{\nu_d} \cdot \frac{W}{W} = \frac{P_S}{P_d} WT, \tag{10.2}$$

where $P_d = \nu_d W$ .

Value B=WT is named a base of a signal. It is visible, that the more base, the more size q, i.e. jamproof of the information system is higher.

Range of information system action directly depends on a jamproof level. Range of action of communication systems, radio broadcasting, TV, control is meant a distance between the transmitter and the receiver at which the information is transferred with small number of mistakes.

In a radar-location this distance is equal to the sum of distances transmitter - object of a location and object of location – receiver. Range of action of communication systems, radio broadcasting, TV, control is directly proportional to size $\sqrt{q}$, that is for its increase it is required to increase power relation signal / disturbance and signal base. Thus, information systems will have the big transfer In a radar-location this distance is equal to the sum of distances transmitter - object of a location and object of location – receiver. capacity, high jamproof and the big range of action if they have high power and wide-band of working frequency.

For calculation of characteristics of information systems and comparisons of systems with various transmitters the equations of range of action of systems is more applicable. The equation of range of a radio communication (the same equation is used for systems of broadcasting, TV, telecontrol and navigation and it is described by equation (10.3):

$$R_C^2 = \frac{P_t G_t G_r \lambda^2 \gamma}{(4\pi)^2 q k T_S \Delta f L N} \tag{10.3}$$

Where:

Rc – a distance between transmitter and receiver of the radio-communication line;

Pt – transmitter radiation power;

$\Delta_f$ – receiver frequency band;

$\lambda$ - radiation wave length;

N - number of communication channels;

Gt и Gr – amplification factors of transmitting and reception aerials (antennas);

q - discernability factor - the relation of signal energy to spectral density of noise masking interference power at the receiver input at which the given quality of transfer of the information is provided.

k=1.38.10-23 J/K° - Boltzmann's constant;

Ts - noise temperature of receiving system;

$\gamma$ - multiplier of ground and troposphere influence.

Using the given relations, we can estimate the efficiency of plasma TWT application in the satellite communication system. Let's consider the system of telecommunication consisting of ground transmitting-receiving stations group and a space retransmitter, occupied the standard high-elliptical orbit with a height R = 40 thousand km. Assume that the system has the following specifications:

wave radiation length $\lambda$=5 cm; amplification factor of transmitting aerial at the ground station antenna $G_t=10^4$; amplification factor of the receiving aerial of a retransmitter antenna $G_r=10^2$; the frequency band allocated for one telephone channel $\delta_f$=20 kHz.

Let's assume, that the ground transmitter uses the TWT of type VTC-6369C2 (manufactured by CPI company) with Pt=2 kW and a working frequency band Wt=500 MHz. With it we shall receive the maximum number of working channels is equal N=2825.

In the case of using the plasma TWT with $P_t$ = 20 kW, $W_t$ = 1000 MHz (f/f = 15%) the maximum number of communication channels will be equal N = 28250, i.e. information capacity of system will raise by 10 times.

Estimations show, that at constant number of channels (T = 2825) due to increase of power and width of frequency band the jamproof of communication will increase by 20 times with use of plasma TWT in comparison with use TWT of type VTC-6369C2.

The basic peculiarity of tropospheric radiorelay communication lines (RRCL), is that sending - receiveing points are on the distances considerably exceeding range of direct visibility is, therefore communication between them is provided due to dispersion of electromagnetic oscillations by tropospheric inhomogenity. The basic part of energy, radiated by the transmitter, dissipates in space, therefore for maintenance of steady communication RRCL transmitters have the big power (10 - 20 kW). Such power is provided now by klystrons, having relative wide-bandwidth 3-5 %.

For suppression the signals fading caused by change of conditions of radio-waves propagation, communication is provided simultaneously on two and more frequencies, therefore with other things being equal, the number of channels in RRCL by 2 and more times is less, than in a usual radiorelay line. Besides for increase of stability it is desirable, that carrier frequencies separation was big enough.

In connection with this is represented expedient to use in RRCL the amplifiers on the basis of plasma TWT . With rated power close to klystron power, they have higher frequency band (~ 5-20 %). Therefore RRCL with transmitters on the base of plasma TWT can have number of channels as a minimum by 4 times more, than with transmitters on klystrons. Besides it is possible to increase carrier frequencies separation and due to this to increase stability of communication.

Thus, application transmitters on the basis of beam-plasma devices (TWT) in radio engineering systems allows:

- to increase number of channels in systems of a radio communication as a minimum by the order;
- to increase significantly stability of work and information capacity of tropospheric radiorelay communication lines;
- to increase essentially jamproof of communication systems.

# XI. The opportunity of application of wide-band plasma TWT for microwave heating of materials with changeable properties

Developed in VEI powerful broad-band beam-plasma amplifiers can find application in microwave power engineering [11.1] where other microwave sources are used now, mainly magnetrons having a narrow working frequency band. The new highly effective light sources on the basis of microwave technology are actively being developed. Studying of molecular radiation spectrum of sulfur in the microwave discharge has allowed to create new highly effective (80-120 lm/W) sources of visible light with the spectral characteristics close to a sunlight. In such devices parameters of gas discharge plasma render influence on own frequency of the resonator modes.

Therefore the important question is the maintenance of magnetron steady work on loading with variable entrance resistance. In a case of discharge initiation instability of work of a microwave system is connected to change of own frequency of the working chamber because of change of the relative dielectric constant environment, and also because of thermal expansion of the resonator case. The increase of frequency instability leads to reduction of transfer of microwave power from the generator to the resonator that demands development of special devices of fine tuning and stabilization of frequency of magnetron, having the limited frequency range [11.2]. Application of powerful broadband plasma TWT will allow to solve the given problem.

The monography [11.1] contains the detailed description of some installations of power engineering microwave devices of continuous operation modes. The analysis of the basic characteristics of resonator-type and wave-guide-type installations is given. Usually the processable materials are imperfect conductors or imperfect dielectrics. Microwave power losses in materials are determined by their physical properties. Some examples of the decision of microwave technology problems known from electrodynamics on power losses in the filling wave-guide lines and resonators filled with imperfect dielectrics and also on energy transfer to dielectric filling media are given. Analysis of physical principles of microwave power absorption justifies that ability and efficiency of installations are determined by dielectric properties of processable materials, their dependence on temperature and structure, and also on geometry of materials. In microwave installations of resonant type it is especially necessary to take into account changes of own frequency of the working chamber at heating of the processable products and change of its volumetric loading in order the change of own frequency of the chamber did not exceed a range of working frequency of the feeding generator.

One of the perspective directions of use of microwave energy in the field of material engineering is sintering of heat resisting and refractory compositions, high-temperature microwave

heating of imperfect dielectrics and also development of microwave plants for crushing of mineral fuel [11.2]. Such microwave plants for fine crushing of cheap minerals coals are perspective for wide introduction in the electric power industry since such technology allows to carry out replacement of black oil fuel with a coal dust or its partial replacement due to burning the black oil – dust coal mixes. Estimations show, that efficiency of such technology process with use of magnetrons strongly depends on factor of volumetric filling of the resonator. So with efficiency equal to 90 % the volumetric filling factor of the resonator makes only 0.55 % that reduces productivity of the given plants (devices). That is why application of the broadband plasma TWT in such plants are very actual.

Increase of the working frequency band of the microwave oscillation source in comparison with magnetrons leads to considerable increase self-oscillation in the working chamber on close frequencies (for example in the chamber made as a prism resonator) which creates a favorable conditions for development microwave installations in the wide range of their loading characteristics. With it the technological system can be controlled with taking into account resonance frequencies change by wave-guides of rectangular cross-section.

At present the basic element of the high-temperature microwave heaters is the high-frequency resonator, supplied from the microwave generator on the base of magnetron working in the continuous operation mode. Profitability and productivity of heating installation determine requirements to the microwave generator and to the resonator system design.

The carried out estimation of opportunities of high-temperature microwave heaters also shows, that the relation of a working body volume to the resonator volume makes ~ 1 %, that is dictated substantially by necessity of maintenance of work of resonant system on loading with variable entrance resistance because of essential temperature dependence of volume, a specific thermal capacity, conductivity, dielectric permeability and other parameters of heated samples [11.2.] Usually typical range of working temperatures at sintering makes 1200-1500K. However there is a whole class of problems when processes proceed at considerably higher temperatures (2000-3000K).

Research works on practical application of microwave heating technology for synthesizing of various ceramics are given in [11.4, 11.5].

It is of special interest of plasma TWT application to have an opportunity to control parameters of non-equilibrium plasma of microwave discharge with help of modulation of electromagnetic oscillation frequencies. Such effects can find application in the modern plasma chemical reactors as they will allow to increase electromagnetic energy input into non-equilibrium plasma of microwave discharge [11.6].

It is very actual also to carry out investigations of transformation ion flows of microwave discharge generated with help of plasma TWT in the non-uniform magnetic field with aim of its application in plasma technologies for treatment of solid materials.

In this case frequency modulation allows not only to change electron temperature in the microwave plasma discharge, but also to control space discharge configuration and ion energy in the plasma beam [11.6].

Development of the beam-plasma amplifier with rated power more than 10 kW, with a working frequency band of 20-25 % including industrial frequency 2,45 GHz, will allow to expand the possible technological applications of actively developing microwave power engineering.

The beam-plasma microwave amplifiers with a set of parameters controlled on the required law (power, frequency band, amplification factor, electronic efficiency ) not having analogues in a traditional vacuum microwave electronics, are perspective for introduction in the microwave power engineering [11.1,11.2,11.3,11.6].

**References:**

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# XII. Conclusion

Researches of plasma filled slow wave structures (SWS) and also microwave characteristics of the developed plasma TWT breadboard models are carried out. Researches of characteristics were carried out on model samples of plasma TWT, intended for the technological purposes with working range at the average industrial frequency 2,45 GHz with an opportunity of expansion frequency band.

As a result of progress in hybrid SWS researches and study of plasma TWT characteristics the following conclusions were made:

- The working frequency band of plasma TWT is determined basically by characteristics of the chain of series connected resonators forming SWS structure. The working frequency band is located in the borders obtained at calculation of vacuum TWT versions. Filling by plasma of the structure central channel increases the amplification factor and output power in the high-frequency part of the frequency spectrum. As result the real frequency band in plasma operation mode of TWT is essentially extended.

- The resonators characteristics research technique is developed at introduction in resonators channel a glow discharge lamp with plasma concentration like in the really working plasma TWT. It was observed a shift of resonators VSWR range in the high-frequency area. In the complete CCC system with terminal devices only HF border is shifted which result in expanding of frequency band.

- The dominate role of dispersion properties of CCC in output plasma TWT characteristics requires application of the perfect methods of dispersion characteristics and interaction impedance calculation at development of plasma TWT. The account of plasma dielectric parameters during calculation allows to estimate the shift of a working frequency band border. The technique of plasma dielectric parameters investigations at calculation of dispersion characteristics should be improved in further.

- It is necessary to take into account, that the calculated CCC structure with the working frequency band exceeding 25÷20 % have a few narrow real range. The matter is a self-excitation of oscillations at edges of the working frequency band. Therefore, it is reasonably to assume the maximum working frequency band in a plasma operation mode of TWT not exceeding 20 %.

- It is possible to ascertain that the basic plasma TWT parameters obtained for today are:

- In a vacuum operation mode:
  output power - 8 kW;
  working frequency band $\Delta f/f =$ 12% ;
  efficiency = 12 %.

- In a plasma operation mode:
  Output power - 16 kW,
  working frequency band $\Delta f/f = 20\%$;
  efficiency - 25 %.

Such combination of key parameters as far as we know, essentially exceeds the results achieved by development of modern vacuum TWT and it is higher than the parameters achieved for today in the multi-resonant klystrons.

- Study of amplified signal characteristics shows, that plasma TWT do not concede the amplification quality of modern vacuum high-power TWT. Plasma TWT have linearity of the amplification factor in the wide range of signals power, and small level of inter-modulation and cross-modulation excitations. Radiations on higher harmonics is also insignificant (-50 dB on frequency of the 2-nd harmonic).

- Study of noise have shown, that inside a working frequency band there is no addition excited oscillations in a plasma operation mode and the noise level in relation to the maximum output signal power is of -57 dB. That is not higher than noise level of powerful vacuum TWT. It is necessary to take into account, that in a pulse-frequency operation mode there are oscillations arise caused by change of a voltage on a pulse fronts. They can be estimated in a researched frequency band by a level less, than - 45 dB in relation to the maximum output signal power.

- Study of a transmitted signal quality and noise level of plasma TWT show, that they can be used in the power output cascades of communication systems. However, for the realization of this problem the additional researches should be carried out with study conditions of self-excitation of oscillations and phase characteristics, with reference to parameters and requirements of concrete communication system. Advantages which can be achieved in the satellite and tropospheric communication systems by use of high-power and broad-band frequency plasma TWT are analyzed.

- The essential positive effect can be achieved at use plasma TWT in the technological purposes. The level of power 10÷20 kW is already sufficient for realization of high-efficiency technological processes, and frequency scanning allows to expect for essential increase of its efficiency in comparison with use of frequency narrow-band magnetrons.

- Special interest of plasma TWT application is connected to an opportunity of control of parameters of non-equilibrium microwave discharge plasma with the help of frequency modulation of electromagnetic oscillations. The given effects can find application in the modern plasma-chemistry reactors as they will allow to increase efficiency of electromagnetic energy contribution in non-equilibrium plasma of microwave discharge. They are actual also the researches of formation

of the directed microwave discharge plasma streams generated by means of plasma TWT in a non-uniform magnetic field, with the purpose of application in plasma technologies for treating and processing of a surface of a solid bodies.

- Ways of realization of technological processes with frequency scanning also as plasma TWT application in the power output cascades of communication systems should become a subject of the further researches.